



US006338127B1

(12) **United States Patent**  
**Manning**

(10) **Patent No.:** **US 6,338,127 B1**  
(45) **Date of Patent:** **Jan. 8, 2002**

(54) **METHOD AND APPARATUS FOR RESYNCHRONIZING A PLURALITY OF CLOCK SIGNALS USED TO LATCH RESPECTIVE DIGITAL SIGNALS, AND MEMORY DEVICE USING SAME**

Alvarez, J. et al. "A Wide Bandwidth Low-Voltage PLL for PowerPC™ Microprocessors" IEEE IEICE Trans. Electron., vol. E-78. No. 6, Jun. 1995, pp. 631-639.

(List continued on next page.)

(75) Inventor: **Troy A. Manning**, Meridan, ID (US)

*Primary Examiner*—Matthew Kim

(73) Assignee: **Micron Technology, Inc.**, Boise, ID (US)

*Assistant Examiner*—Matthew D. Anderson

(74) *Attorney, Agent, or Firm*—Dorsey & Whitney LLP

(\* ) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(57) **ABSTRACT**

A system adaptively adjusts the phases of a plurality of internal clock signals, each respective internal clock signal causing a corresponding latch to store a digital signal responsive to the respective internal clock signal. The system includes a plurality of clock control circuits, each clock control circuit controlling the phase of a respective internal clock signal relative to a corresponding external clock signal responsive to a respective phase command signal. A plurality of evaluation circuits are coupled to the respective latches, each comparing the plurality of digital signals stored in the corresponding latch to expected values and generating a result signal indicating the results of this comparison. A phase selector circuit operates in a storage mode to sequentially develop a plurality of phase command signals on an output and store a corresponding result signal sequentially received on an input. The phase selector operates in an analysis mode to develop on the output a final phase command signal from the stored result signals. A plurality of storage circuits are coupled to respective clock control circuits and to the output of a selector circuit. Each storage circuit stores the final phase command signal responsive to a corresponding clock domain signal. A clock-domain control circuit develops a plurality of clock domain signals to control the evaluation, storage, and phase selector circuits to sequentially synchronize each internal clock signal. The clock-domain control circuit operates to perform partial synchronization of the clock signals after all clock signals have once been synchronized during a power-up submode of operation.

(21) Appl. No.: **09/143,033**

(22) Filed: **Aug. 28, 1998**

(51) **Int. Cl.**<sup>7</sup> ..... **C06F 12/00**

(52) **U.S. Cl.** ..... **711/167; 713/400**

(58) **Field of Search** ..... 711/167, 105, 711/109, 114, 150; 713/400; 326/93, 96, 99; 375/354

(56) **References Cited**

**U.S. PATENT DOCUMENTS**

3,633,174 A 1/1972 Griffin  
4,077,016 A 2/1978 Sanders et al.  
4,096,402 A 6/1978 Schroeder et al.

(List continued on next page.)

**FOREIGN PATENT DOCUMENTS**

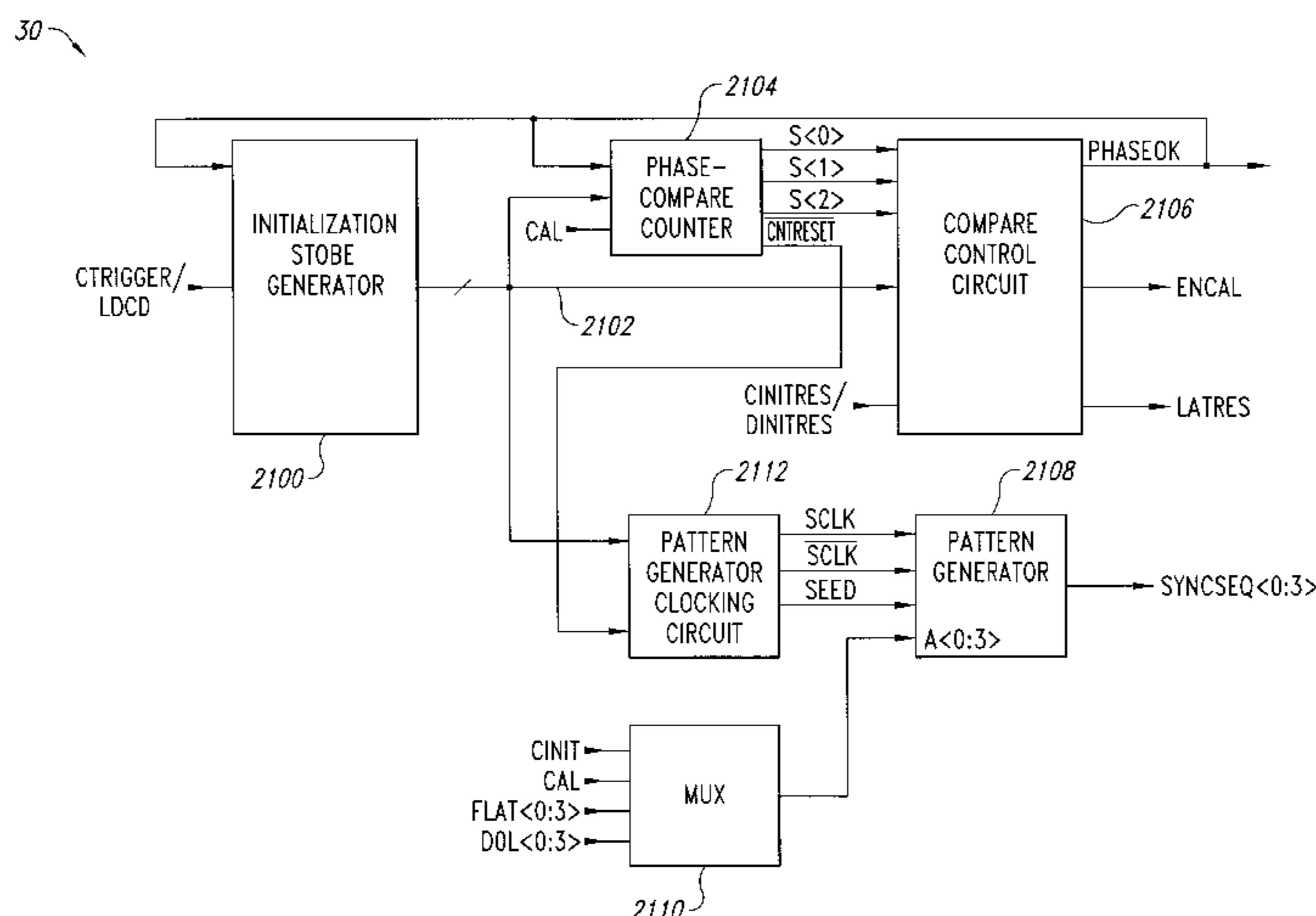
EP 0 171 720 A2 2/1986  
EP 0 295 515 A1 12/1988  
EP 0 406 786 A1 1/1991

(List continued on next page.)

**OTHER PUBLICATIONS**

Gustavson, David B., et al., IEEE Standard for Scalable Coherent Interface (SCI), IEEE Computer Society, IEEE Std. 1596-1992, Aug. 2, 1993.

**35 Claims, 16 Drawing Sheets**



U.S. PATENT DOCUMENTS					
4,404,474 A	9/1983	Dingwall	5,408,640 A	4/1995	MacIntyre et al.
4,481,625 A	11/1984	Roberts et al.	5,410,263 A	4/1995	Waizman
4,508,983 A	4/1985	Allgood et al.	5,416,436 A	5/1995	Rainard
4,511,846 A	4/1985	Nagy et al.	5,416,909 A	5/1995	Long et al.
4,514,647 A	4/1985	Shoji	5,420,544 A	5/1995	Ishibashi
4,524,448 A	6/1985	Hullwegen	5,428,311 A	6/1995	McClure
4,573,017 A	2/1986	Levine	5,428,317 A	6/1995	Sanchez et al.
4,600,895 A	7/1986	Landsman	5,430,408 A	7/1995	Ovens et al.
4,603,320 A	7/1986	Farago	5,430,676 A	7/1995	Ware et al.
4,636,187 A	1/1987	Boler et al.	5,432,823 A	7/1995	Gasbarro et al.
4,638,451 A	1/1987	Hester et al.	5,438,545 A	8/1995	Sim
4,687,951 A	8/1987	McElroy	5,440,260 A	8/1995	Hayashi et al.
4,773,085 A	9/1988	Cordell	5,440,514 A	8/1995	Flannagan et al.
4,789,796 A	12/1988	Foss	5,444,667 A	8/1995	Obara
4,818,995 A	4/1989	Takahashi et al.	5,446,696 A	8/1995	Ware et al.
4,893,087 A	1/1990	Davis	5,448,193 A	9/1995	Baumert et al.
4,902,986 A	2/1990	Lesmeister	5,451,898 A	9/1995	Johnson
4,953,128 A	8/1990	Kawai et al.	5,457,407 A	10/1995	Shu et al.
4,958,088 A	9/1990	Farah-Bakhsh et al.	5,465,076 A	11/1995	Yamauchi et al.
4,972,470 A	11/1990	Farago	5,473,274 A	12/1995	Reilly et al.
4,984,204 A	1/1991	Sato et al.	5,473,575 A	12/1995	Farmwald et al.
5,020,023 A	5/1991	Smith	5,473,639 A	12/1995	Lee et al.
5,038,115 A	8/1991	Myers et al.	5,485,490 A	1/1996	Leung et al.
5,075,569 A	12/1991	Branson	5,488,321 A	1/1996	Johnson
5,086,500 A	2/1992	Greub	5,489,864 A	2/1996	Ashuri
5,087,828 A	2/1992	Sato et al.	5,497,127 A	3/1996	Sauer
5,122,690 A	6/1992	Bianchi	5,498,990 A	3/1996	Leung et al.
5,128,560 A	7/1992	Chern et al.	5,500,808 A	3/1996	Wang
5,128,563 A	7/1992	Hush et al.	5,506,814 A	4/1996	Hush et al.
5,134,311 A	7/1992	Biber et al.	5,508,638 A	4/1996	Cowles et al.
5,150,186 A	9/1992	Pinney et al.	5,513,327 A	4/1996	Farmwald et al.
5,165,046 A	11/1992	Hesson	5,532,714 A	7/1996	Knapp et al.
5,179,298 A	1/1993	Hirano et al.	5,539,345 A	7/1996	Hawkins
5,194,765 A	3/1993	Dunlop et al.	5,544,124 A	8/1996	Zagar et al.
5,212,601 A	5/1993	Wilson	5,544,203 A	8/1996	Casasanta et al.
5,220,208 A	6/1993	Schenck	5,552,727 A	9/1996	Nakao
5,223,755 A	6/1993	Richley	5,555,429 A	9/1996	Parkinson et al.
5,233,314 A	8/1993	McDermott et al.	5,557,224 A	9/1996	Wright et al.
5,233,564 A	8/1993	Ohshima et al.	5,557,781 A	9/1996	Stones et al.
5,239,206 A	8/1993	Yanai	5,563,546 A	10/1996	Tsukada
5,243,703 A	9/1993	Farmwald et al.	5,568,075 A	10/1996	Curran et al.
5,254,883 A	10/1993	Horowitz et al.	5,568,077 A	10/1996	Sato et al.
5,256,989 A	10/1993	Parker et al.	5,572,557 A	11/1996	Aoki
5,257,294 A	10/1993	Pinto et al.	5,572,722 A	11/1996	Vogley
5,268,639 A	12/1993	Gasbarro et al.	5,574,698 A	11/1996	Raad
5,272,729 A	12/1993	Bechade et al.	5,576,645 A	11/1996	Farwell
5,274,276 A	12/1993	Casper et al.	5,577,236 A	11/1996	Johnson et al.
5,276,642 A	1/1994	Lee	5,578,940 A	11/1996	Dillon et al.
5,278,460 A	1/1994	Casper	5,578,941 A	11/1996	Sher et al.
5,281,865 A	1/1994	Yamashita et al.	5,579,326 A	11/1996	McClure
5,283,631 A	2/1994	Koerner et al.	5,581,197 A	12/1996	Motley et al.
5,289,580 A	2/1994	Latif et al.	5,589,788 A	12/1996	Goto
5,295,164 A	3/1994	Yamamura	5,590,073 A	12/1996	Arakawa et al.
5,304,952 A	4/1994	Quiet et al.	5,594,690 A	1/1997	Rothenberger et al.
5,311,481 A	5/1994	Casper et al.	5,614,855 A	3/1997	Lee et al.
5,311,483 A	5/1994	Takasugi	5,619,473 A	4/1997	Hotta
5,313,431 A	5/1994	Uruma et al.	5,621,690 A	4/1997	Jungroth et al.
5,315,388 A	5/1994	Shen et al.	5,621,739 A	4/1997	Sine et al.
5,321,368 A	6/1994	Hoelzle	5,627,780 A	5/1997	Malhi
5,337,285 A	8/1994	Ware et al.	5,627,791 A	5/1997	Wright et al.
5,341,405 A	8/1994	Mallard, Jr.	5,631,872 A	5/1997	Naritake et al.
5,347,177 A	9/1994	Lipp	5,636,163 A	6/1997	Furutani et al.
5,347,179 A	9/1994	Casper et al.	5,636,173 A	6/1997	Schaefer
5,355,391 A	10/1994	Horowitz et al.	5,636,174 A	6/1997	Rao
5,361,002 A	11/1994	Casper	5,638,335 A	6/1997	Akiyama et al.
5,367,649 A	11/1994	Cedar	5,646,904 A	7/1997	Ohno et al.
5,379,299 A	1/1995	Schwartz	5,652,530 A	7/1997	Ashuri
5,390,308 A	2/1995	Ware et al.	5,657,289 A	8/1997	Hush et al.
5,400,283 A	3/1995	Raad	5,657,481 A	8/1997	Farmwald et al.
5,402,389 A	3/1995	Flannagan et al.	5,663,921 A	9/1997	Pascucci et al.
			5,666,322 A	9/1997	Conkle

5,668,763	A	9/1997	Fujioka et al.
5,668,774	A	9/1997	Furutani
5,675,274	A	10/1997	Kobayashi et al.
5,692,165	A	11/1997	Jeddeloh et al.
5,694,065	A	12/1997	Hamasaki et al.
5,708,611	A	1/1998	Iwamoto
5,712,580	A	1/1998	Baumgartner et al.
5,719,508	A	2/1998	Daly
5,740,123	A	4/1998	Uchida
5,751,665	A	5/1998	Tanoi
5,767,715	A	6/1998	Marquis et al.
5,768,177	A	6/1998	Sakuragi
5,774,699	A	6/1998	Nagae
5,778,214	A	7/1998	Taya et al.
5,781,499	A	7/1998	Koshikawa
5,784,422	A	7/1998	Heermann
5,789,947	A	8/1998	Sato
5,790,612	A	8/1998	Chengson et al.
5,794,020	A	8/1998	Tanaka et al.
5,805,931	A	9/1998	Morzano et al.
5,812,619	A	9/1998	Runaldu
5,822,314	A	10/1998	Chater-Lea
5,831,929	A	11/1998	Manning
5,841,707	A	11/1998	Cline et al.
5,852,378	A	12/1998	Keeth
5,872,959	A	2/1999	Nguyen
5,889,829	A	3/1999	Chiao et al.
5,898,242	A	4/1999	Peterson
5,898,674	A	4/1999	Mawhinney et al.
5,917,760	A	6/1999	Millar
5,920,518	A	7/1999	Harrison et al.
5,926,047	A	7/1999	Harrison
5,926,436	A	7/1999	Toda et al.
5,940,608	A	8/1999	Manning
5,940,609	A	8/1999	Harrison
5,946,244	A	8/1999	Manning
5,953,284	A	9/1999	Baker et al.
5,964,884	A	10/1999	Partovi et al.
5,990,719	A	11/1999	Dai et al.
6,005,823	A	12/1999	Martin et al.
6,011,732	A	1/2000	Harrison et al.
6,016,282	A	1/2000	Keeth
6,026,050	A	2/2000	Baker et al.
6,029,250	A	2/2000	Keeth
6,038,219	A	3/2000	Mawhinney et al.
6,067,592	A	5/2000	Farmwald et al.
6,101,152	A	8/2000	Farmwald et al.
6,101,197	A	8/2000	Keeth et al.
6,105,157	A	8/2000	Miller
6,147,905	A	11/2000	Seino
6,147,916	A	11/2000	Ogura
6,160,423	A	12/2000	Haq

FOREIGN PATENT DOCUMENTS

EP	0 450 871	A2	10/1991
EP	0 476 585	A2	3/1992
EP	0 767 538	A1	4/1994
EP	0 655 741	A2	5/1995
EP	0 655 834	A1	5/1995
EP	0 680 049	A2	11/1995
EP	0 703 663	A1	3/1996
EP	0 704 848	A2	4/1996
EP	0 704 975	A1	4/1996
JP	6-1237512		10/1986
JP	2-11317		4/1990
JP	4-135311		8/1992
JP	5-136664		6/1993
JP	5-282868		10/1993
JP	0-7319577		12/1995
WO	WO 94/29871		12/1994
WO	WO 95/22200		8/1995

WO	WO 95/22206	8/1995
WO	WO 96/10866	4/1996
WO	WO 97/14289	4/1997
WO	WO 97/425557	11/1997

OTHER PUBLICATIONS

Anonymous, "Programmable Pulse Generator", IBM Technical Disclosure Bulletin, vol. 17, No. 12, May 1975, pp. 3553-3554.

Anonymous, "Pulse Combining Network", IBM Technical Disclosure Bulletin, vol. 32, No. 12, May 1990, pp. 149-151.

Anonymous, "Variable Delay Digital Circuit", IBM Technical Disclosure Bulletin, vol. 35, No. 4A, Sep. 1992, pp. 365-366.

Arai, Y. et al., "A CMOS Four-Channel x 1K Time Memory LSI with 1-ns/b Resolution", IEEE Journal of Solid-State Circuits, vol. 27, No.3,M, 8107 Mar., 1992, No. 3, New York, US.

Arai, Y. et al., "A Time Digitizer CMOS Gate-Array with a 250 ps Time Resolution", XP 000597207, IEEE Journal of Solid-State Circuits, vol. 31, No.2, Feb. 1996.

Aviram, A. et al., "Obtaining High Speed Printing on Thermal Sensitive Special Paper with a Resistive Ribbon Print Head", IBM Technical Disclosure Bulletin, Vol. 27, No. 5, Oct. 1984, pp. 3059-3060.

Bazes, M., "Two Novel Fully Complementary Self-Biased CMOS Differential Amplifiers", IEEE Journal of Solid-State Circuits, vol. 26, No. 2, Feb. 1991, pp. 165-168.

Chapman, J. et al., "A Low-Cost High-Performance CMOS Timing Vernier for ATE", IEEE International Test Conference, Paper 21.2, 1995, pp. 459-468.

Cho, J. "Digitally-Controlled PLL with Pulse Width Detection Mechanism for Error Correction", ISSCC 1997, Paper No. SA 20.3, pp. 334-335.

Christiansen, J. et al., "A Low-Cost High-Performance CMOS Timing Generator Based on an Array of Delay Locked Loops", IEEE Journal of Solid-State Circuits, vol. 31, No. 7, Jul. 1996, pp. 952-957.

Combes, M. et al., "A Portable Clock Multiplier Generator Using Digital CMOS Standard Cells", IEEE Journal of Solid-State Circuits, vol. 31, No. 7, Jul. 1996, pp. 958-965.

Descriptive literature entitled, "400MHz SLDRAM, 4M X 16 SLDRAM Pipelined, Eight Bank, 2.5 V Operation," SLDRAM Consortium Advance Sheet, published throughout the United States, pp. 1-22.

Donnelly, K. et al., "A 660 MB/s Interface Megacell Portable Circuit in 0.3  $\mu$ m-0.7  $\mu$ m CMOS ASIC", IEEE Journal of Solid-State Circuits, vol. 31, No. 12, Dec. 1996, pp. 1995-2001.

"Draft Standard for a High-Speed Memory Interface (SyncLink)", Microprocessor and Microprocessor Standard Subcommittee of the IEEE Computer Society, Copyright 1996 by the Institute of Electrical and Electronics Engineers, Inc., New York, NY, pp. 1-56.

Goto, J. et al., "A PLL-Based Programmable Clock Generator with 50-to 350-MHz Oscillating Range for Video Signal Processors", IEICE Trans. Electron., vol. E77-C, No. 12, Dec. 1994, pp. 1951-1956.

Hamamoto, T., "400-MHz Random Column Operating SDRAM Techniques with Self-Skew Compensation, IEEE Journal of Solid-State Circuits, vol. 33, No. 5, May 1998, pp. 770-778.

- Ishibashi, A. et al., "High-Speed Clock Distribution Architecture Employing PLL for 0.6 $\mu$ m CMOS SOG", IEEE Custom Integrated Circuits Conference, 1992 pp. 27.6.1-27.6.4.
- Kim, B. et al., "A 30MHz High-Speed Analog/Digital PLL in 2 $\mu$ m CMOS", ISSCC, Feb 1989.
- Kikuchi, S. et al., "A Gate-Array-Based 666MHz VLSI Test System", IEEE International Test Conference, Paper 21.1, 1995, pp. 451-458.
- Ko, U. et al., "A 30-ps Jitter, 3.6- $\mu$ s Locking, 3.3-Volt Digital PLL For CMOS Gate Arrays", IEEE Custom Integrated Circuits Conference, 1993, pp. 23.3.1-23.3.4.
- Lee, T. et al., "A 2.5V Delay-Locked Loop for an 18Mb 500MB/s DRAM", IEEE International Solid-State Circuits Conference Digest of Technical Papers, Paper No. FA 18.6, 1994, pp. 300-301.
- Lesmeister, G., "A Densely Integrated High Performance CMOS Tester", International Test Conference, Paper 16.2, 1991, pp. 426-429.
- Ljuslin, C. et al., "An Integrated 16-channel CMOS Time to Digital Converter", IEEE Nuclear Science Symposium & Medical Imaging Conference Record, vol. 1, 1993, pp. 625-629.
- Maneatis, J., "Low-Jitter Process-Independent DLL and PLL Based on Self-Biased Techniques", IEEE Journal of Solid-State Circuits, vol. 31, No. 11, Nov. 1996, pp. 1723-1732.
- Nakamura, M. et al., "A 156 Mbps CMOS Clock Recovery Circuit for Burst-mode Transmission", Symposium on VLSI Circuits Digest of Technical Papers, 1996, pp. 122-123.
- Nielson, E., "Inverting latches make simple VCO", EDN, Jun. 19, 1997.
- Novof, I. et al., "Fully Integrated CMOS Phase-Locked Loop with 15 to 240 Mhz Locking Range and  $\pm 50$  ps Jitter", IEEE Journal of Solid-State Circuits, vol. 30, No. 11, Nov. 1995, pp. 1259-1266.
- Saeki, T. et al., "A 2.5-ns Clock Access, 250-MHz, 256-Mb SDRAM with Synchronous Mirror Delay", IEEE Journal of Solid-State Circuits, vol. 31, No. 11, Nov. 1996, pp. 1656-1665.
- Santos, D. et al., "A CMOS Delay Locked Loop And Sub-Nanosecond Time-to-Digital Converter Chip", IEEE Nuclear Science Symposium and Medical Imaging Conference Record, vol. 1, Oct. 1995, pp. 289-291.
- Shirotori, T. et al., "PLL-based, Impedance Controlled Output Buffer", 1991 Symposium on VLSI Circuits Digest of Technical Papers, pp. 49-50.
- Sidiropoulos, S. et al., "A 700-Mb/s/pin CMOS Signaling Interface Using Current Integrating Receivers", IEEE Journal of Solid-State Circuits, vol. 32, No. 5, May 1997, pp. 681-690.
- Sidiropoulos, S. et al., "A CMOS 500 Mbps/pin synchronous point to point link interface", IEEE Symposium on VLSI Circuits Digest of Technical Papers, 1994, pp. 43-44.
- Sidiropoulos, S. et al., "A Semi-Digital DLL with Unlimited Phase Shift Capability and 0.08-400MHz Operating Range," in 1997 IEEE International Solid State Circuits Conference, Feb. 8, 1997, pp. 332-333.
- Soyuer, M. et al., "A Fully Monolithic 1.25GHz CMOS Frequency Synthesizer", IEEE Symposium on VLSI Circuits Digest of Technical Papers, 1994, pp. 127-128.
- Taguchi, M. et al., "A 40-ns-64-Mb DRAM with 64-b Parallel Data Bus Architecture", IEEE Journal of Solid-State Circuits, vol. 26, No. 11, Nov. 1991, pp. 1493-1497.
- Tanoi, S. et al., "A 250-622 MHz Deskew and Jitter-Suppressed Clock Buffer Using a Frequency-and Delay-Locked Two-Loop Architecture", 1995 Symposium on VLSI Circuits Digest of Technical Papers, vol. 11, No. 2, pp. 85-86.
- Tanoi, S. et al., "A 250-622 Mhz Deskew and Jitter-Suppressed Clock Buffer Using Two-Loop Architecture", IEEE IEICE Trans. Electron., vol.E-79-C. No. 7, Jul. 1996, pp. 898-904.
- von Kaenel, V. et al., "A 320 MHz, 1.5mW @ 1.35 V CMOS PLL for Microprocessor Clock Generation", IEEE Journal of Solid-State Circuits, vol. 31, No. 11, Nov. 1996, pp. 1715-1722.
- Watson, R. et al., "Clock Buffer Chip with Absolute Delay Regulation Over Process and Environmental Variations", IEEE Custom Integrated Circuits Conference, 1992, pp. 25.2.1-25.2.5.
- Yoshimura, T. et al. "A 622-Mb/s Bit/Frame Synchronizer for High-Speed Backplane Data Communication", IEEE Journal of Solid-State Circuits, vol. 31, No. 7, Jul. 1996, pp. 1063-1066.

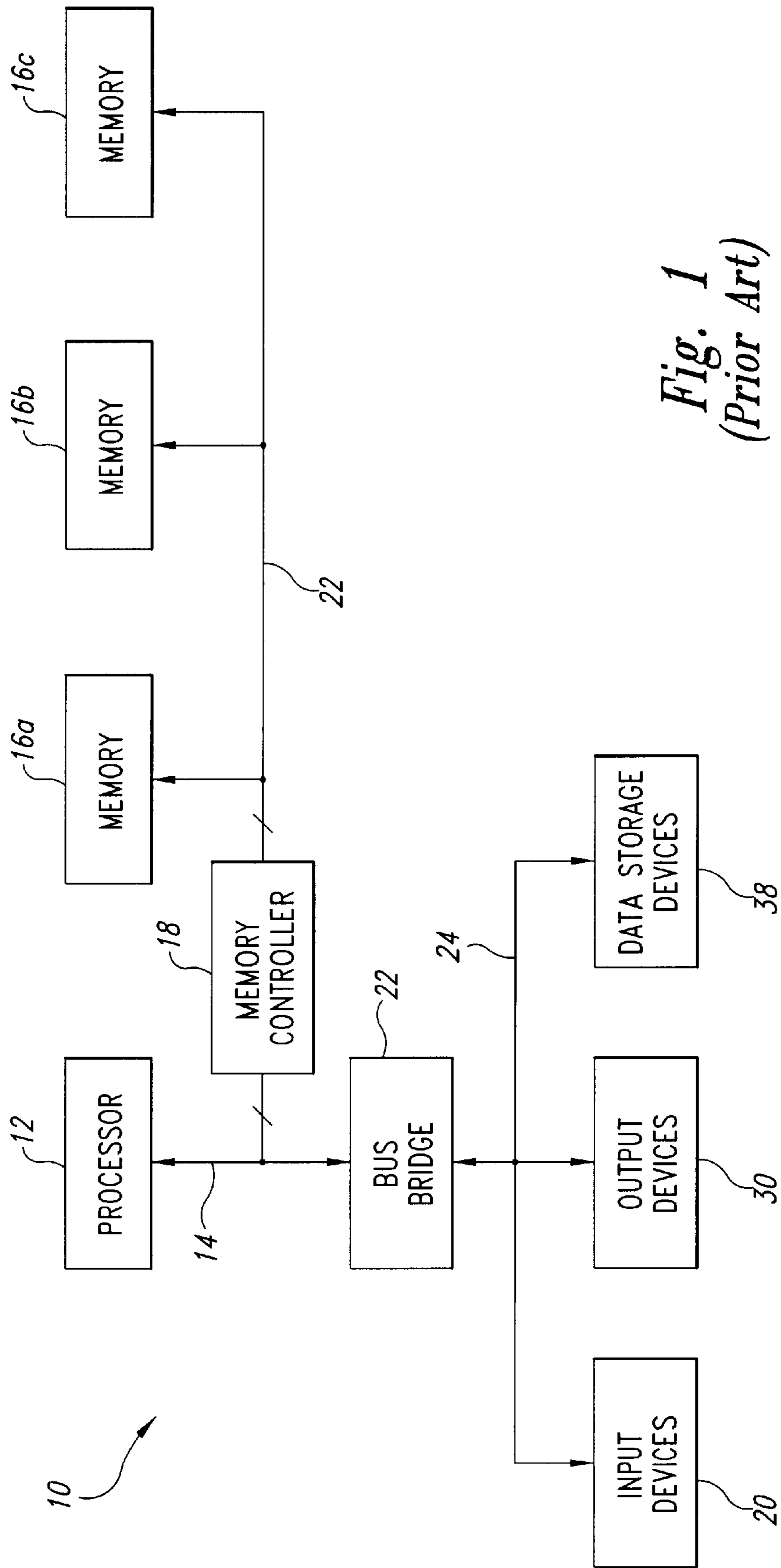
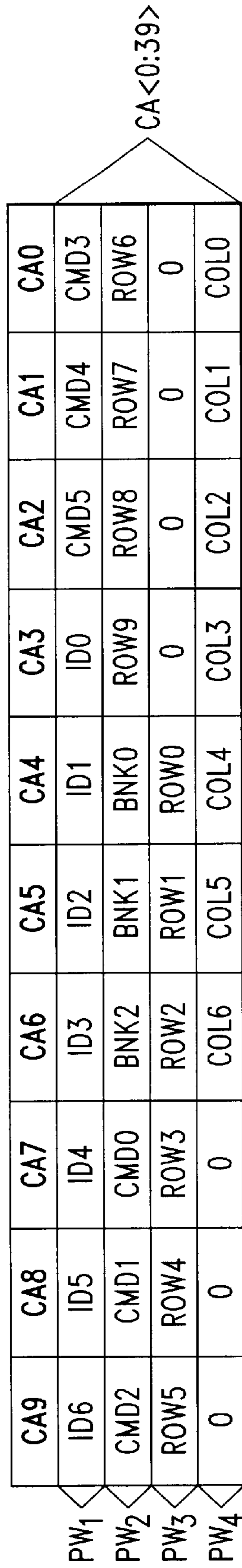


Fig. 1  
(Prior Art)



ID6-ID0 = DEVICE ID VALUE  
 CMD5-CMD0 = COMMAND CODE  
 BNK2-BNK0 = BANK ADDRESS

ROW9-ROW0 = ROW ADDRESS  
 COL6-COLO = COLUMN ADDRESS  
 0 = UNUSED

*Fig. 2*  
*(PRIOR ART)*

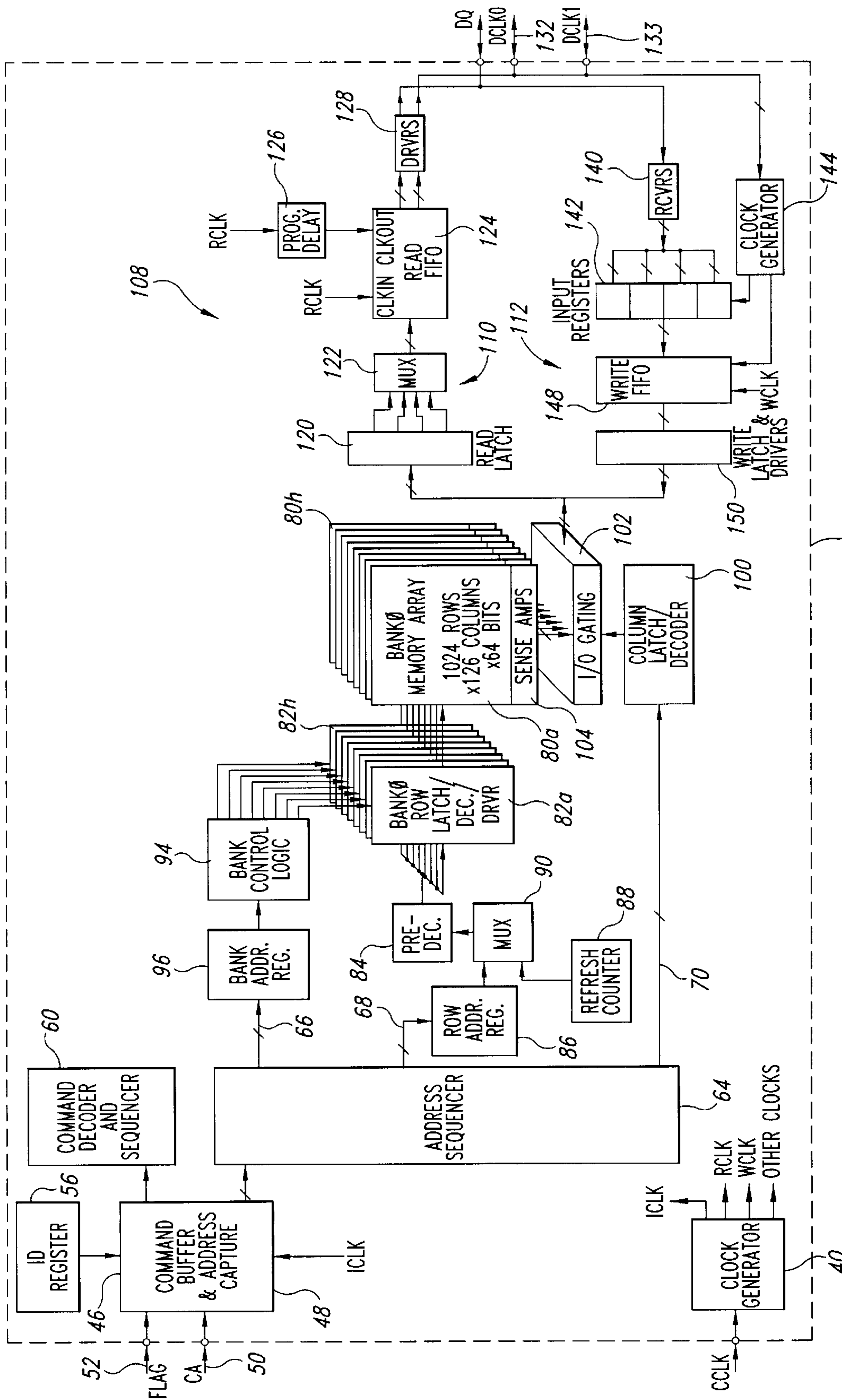
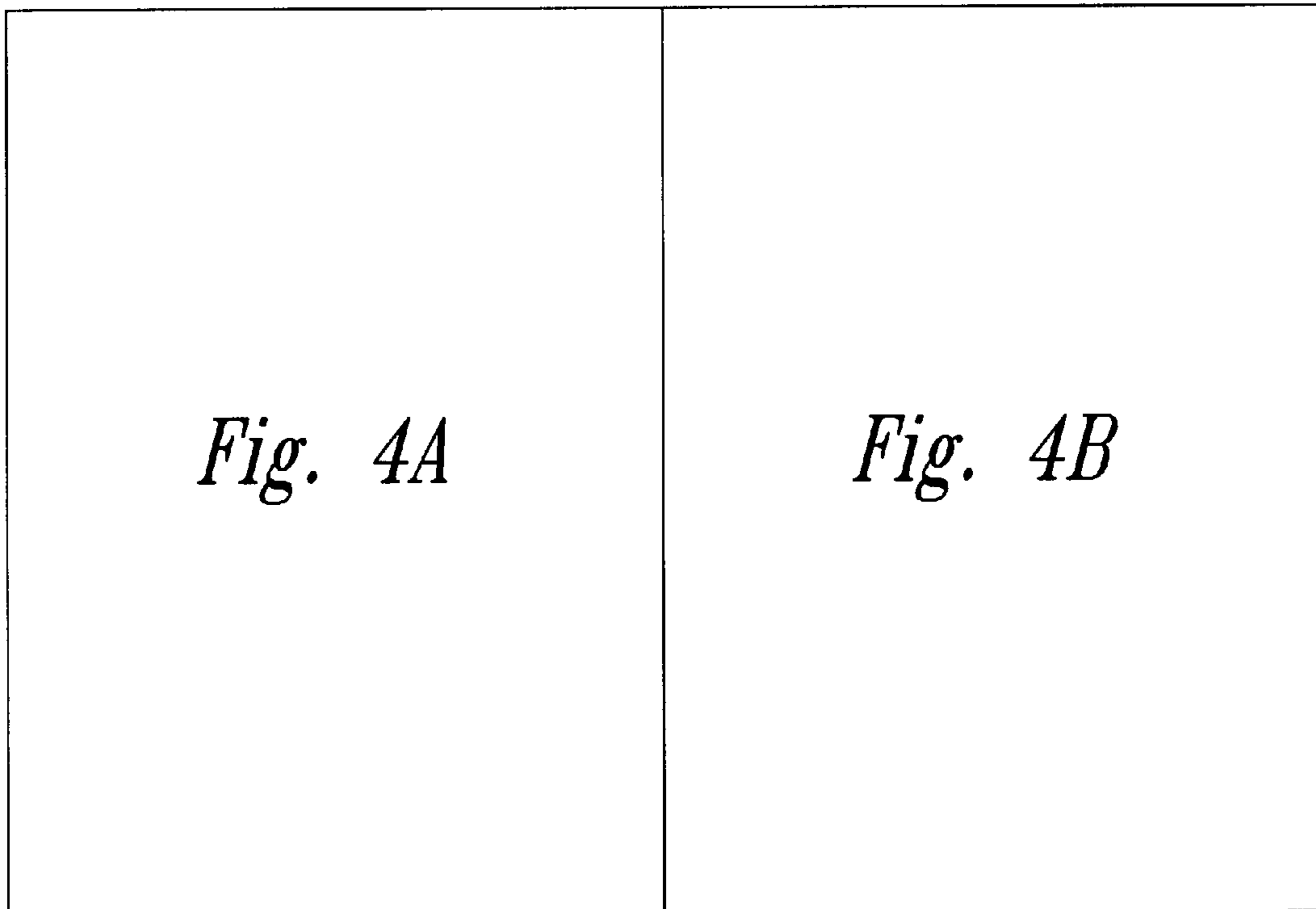


Fig. 3 (PRIOR ART)



*Fig. 4*



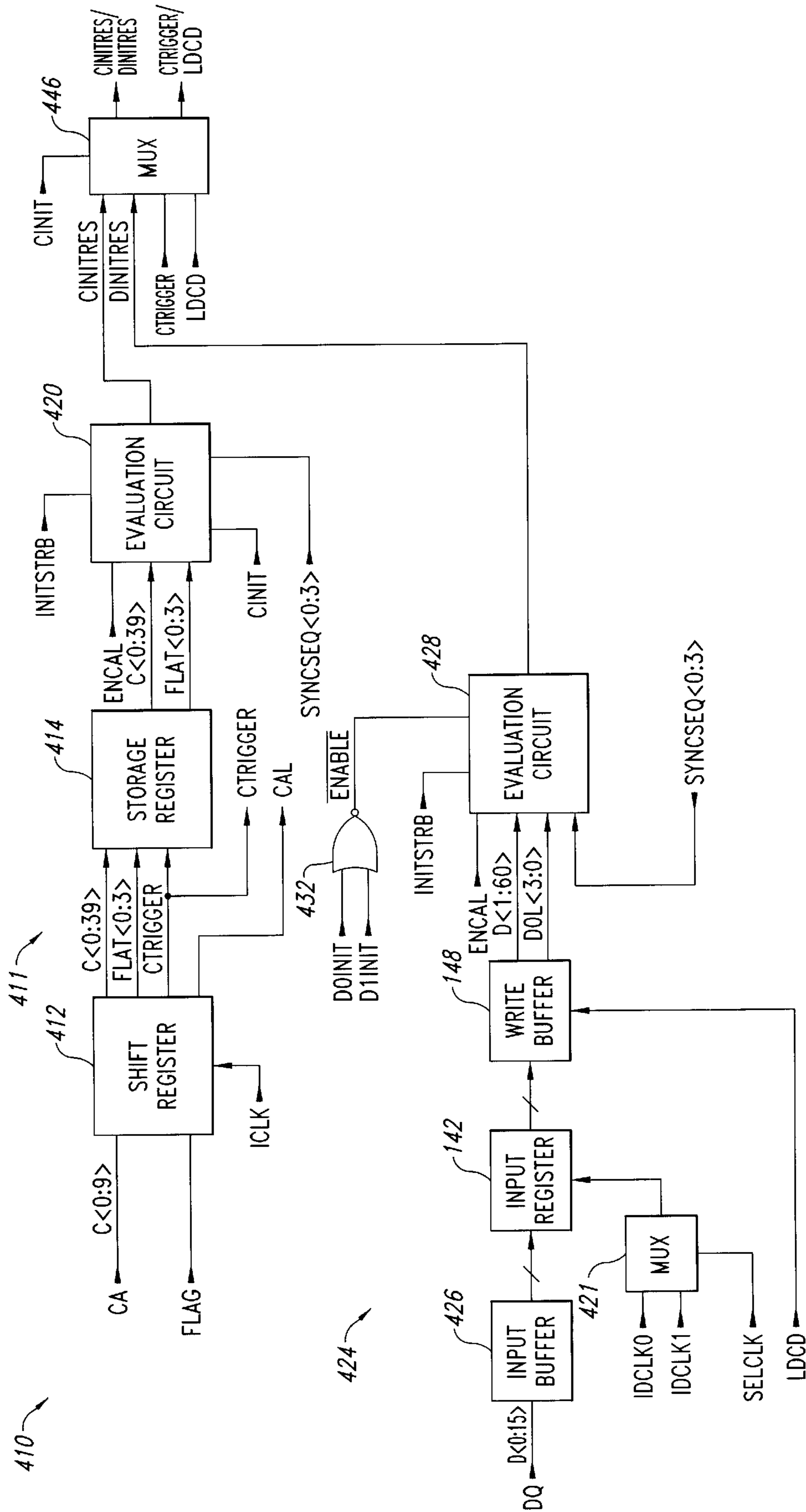


Fig. 4A

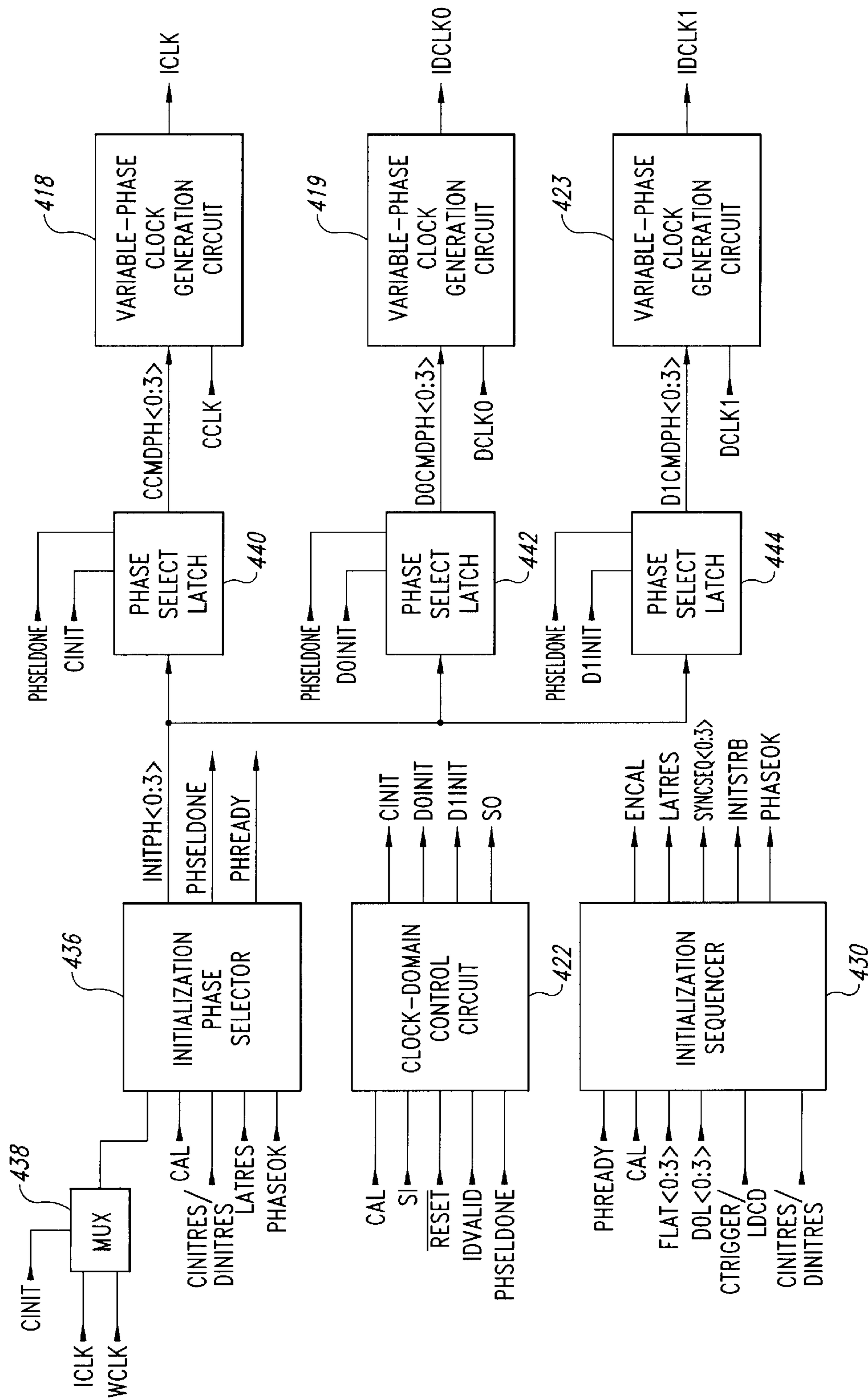


Fig. 4B

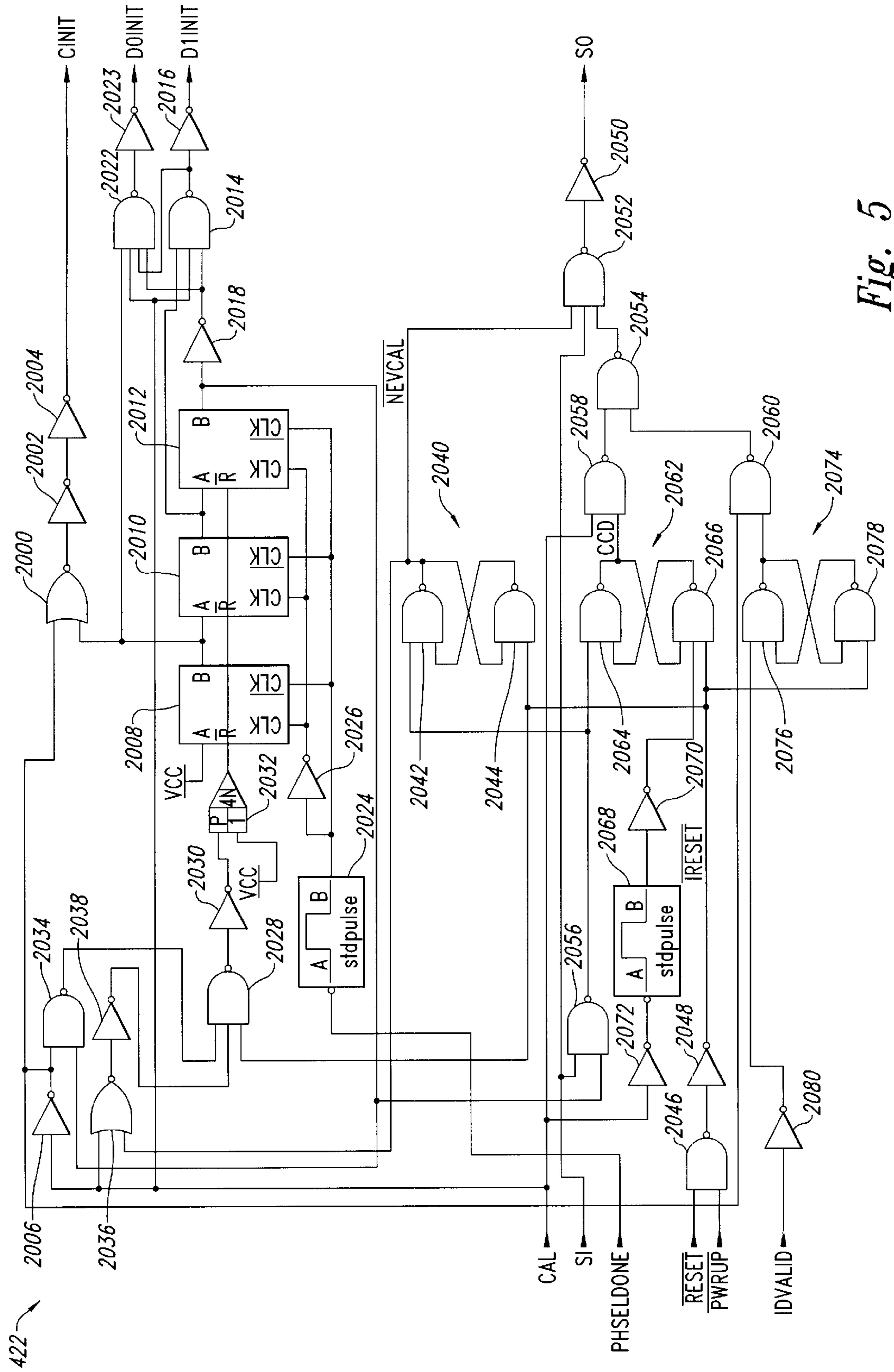


Fig. 5

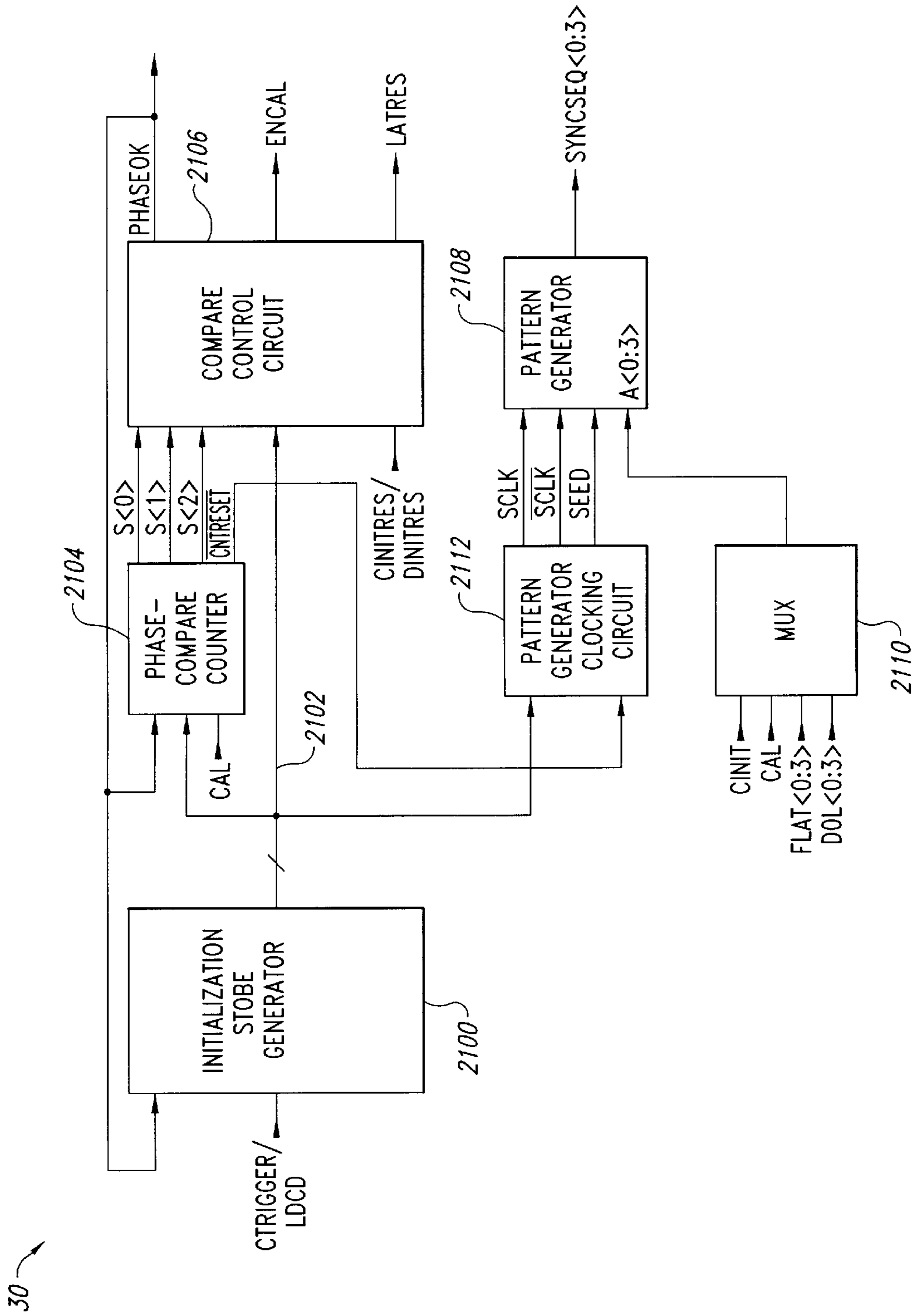


Fig. 6

2100

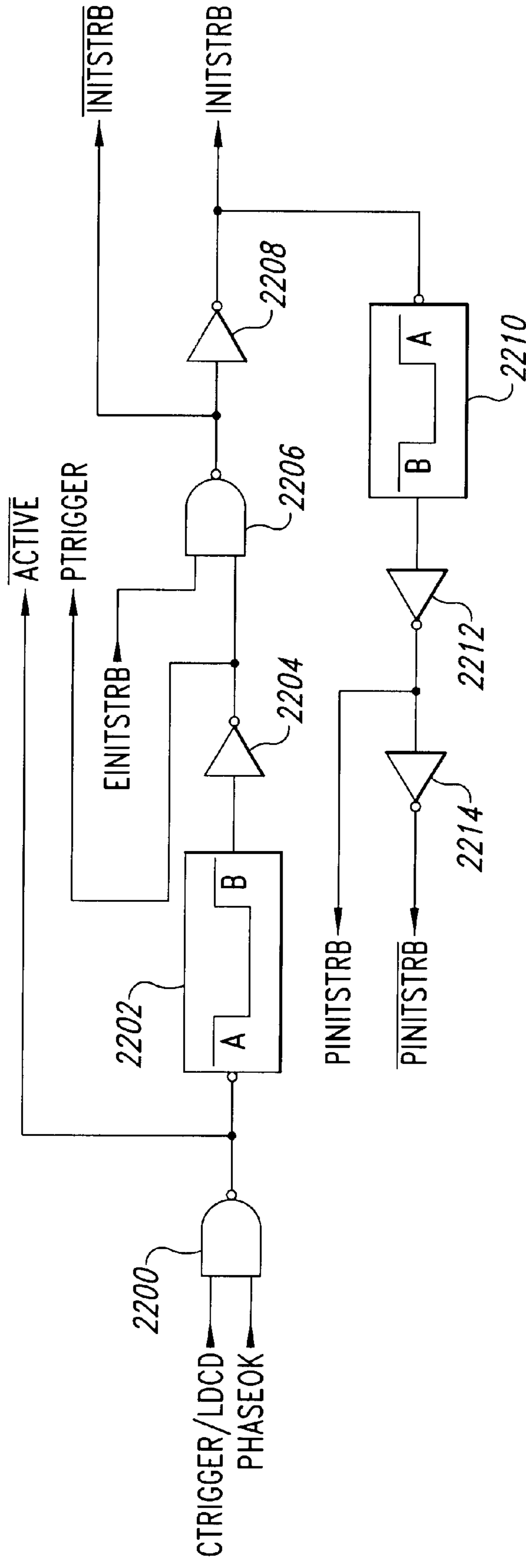


Fig. 7

2104

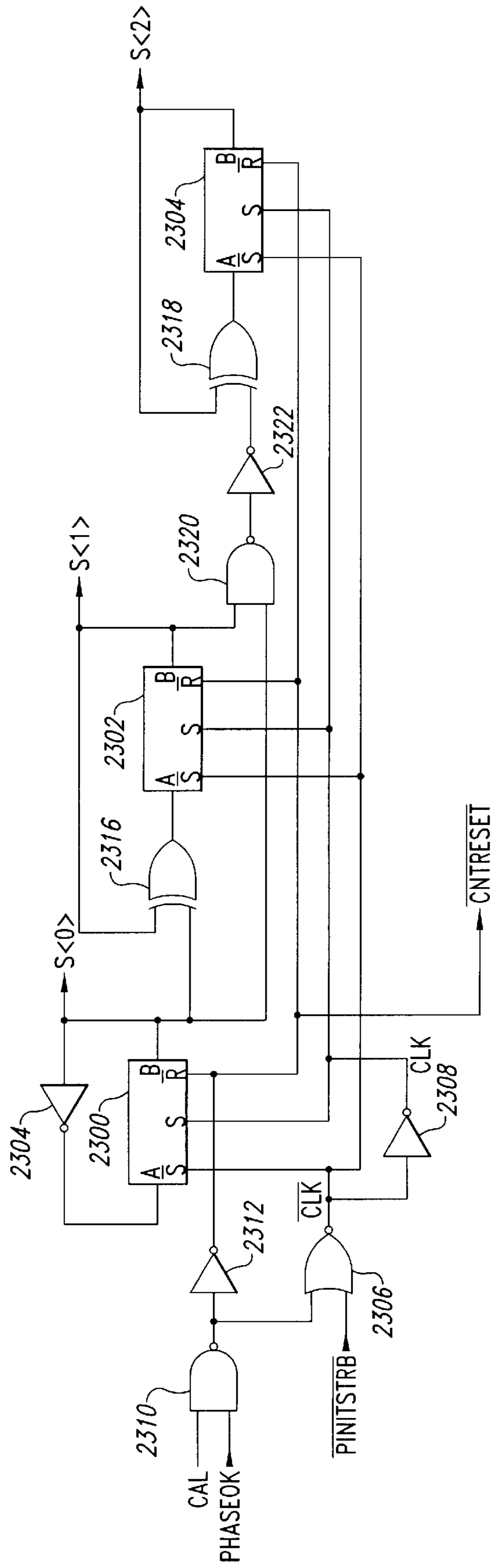


Fig. 8

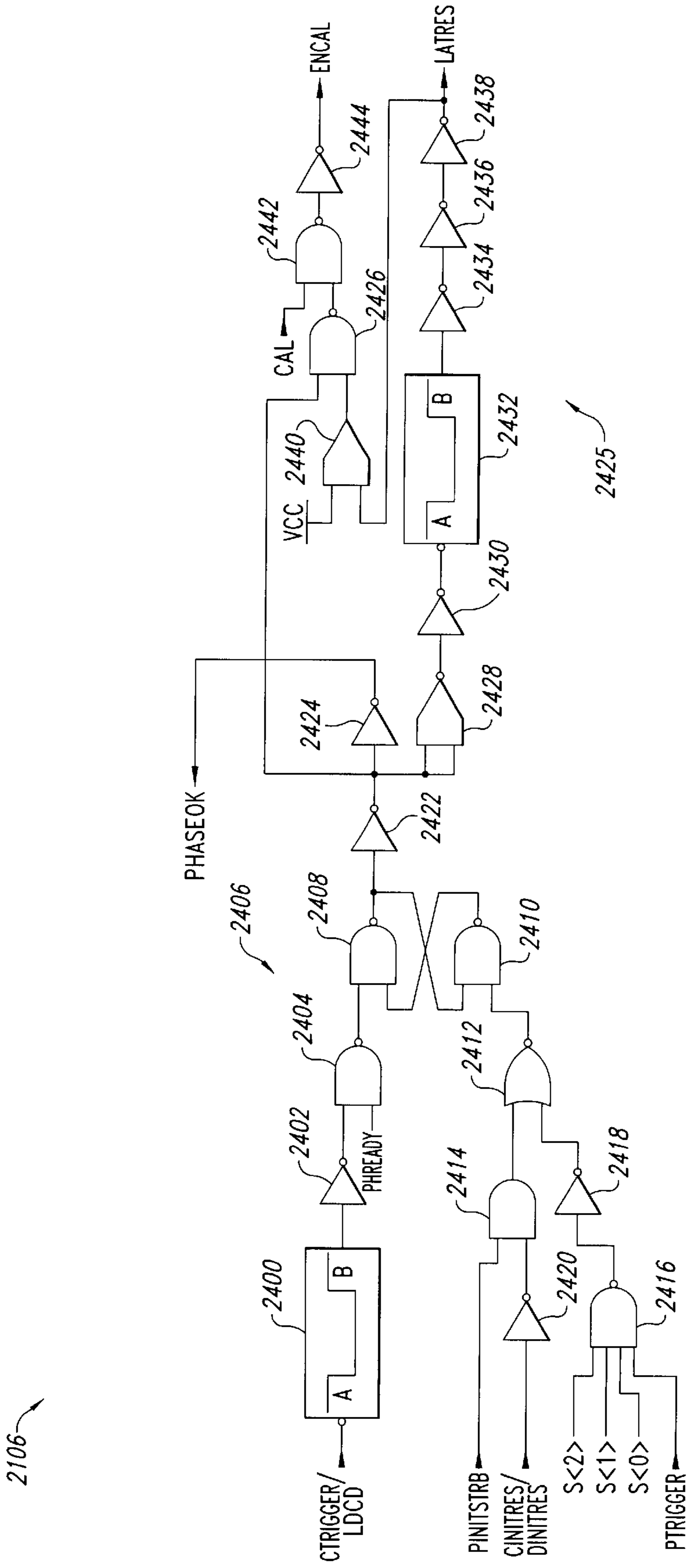


Fig. 9

2110

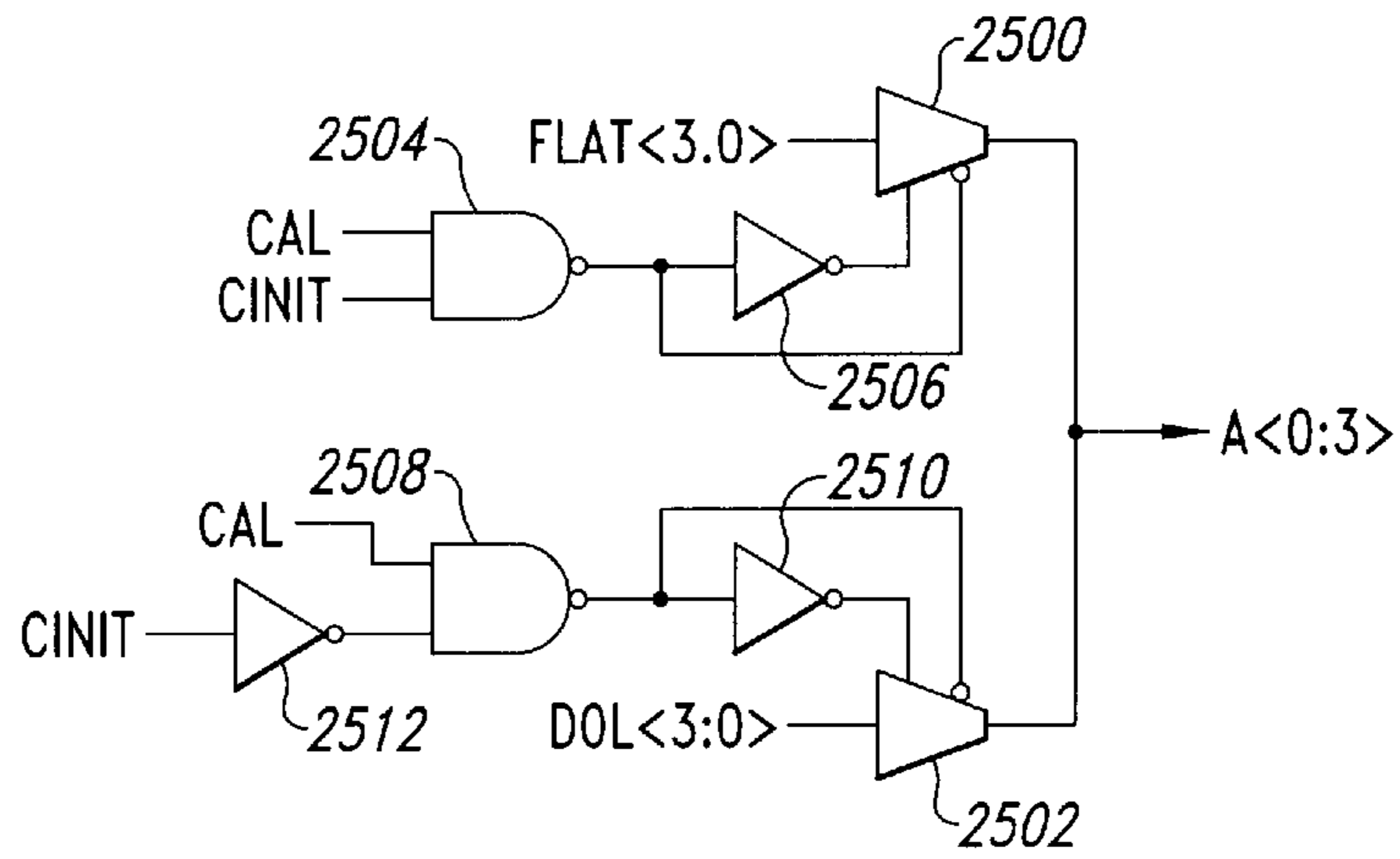


Fig. 10

418

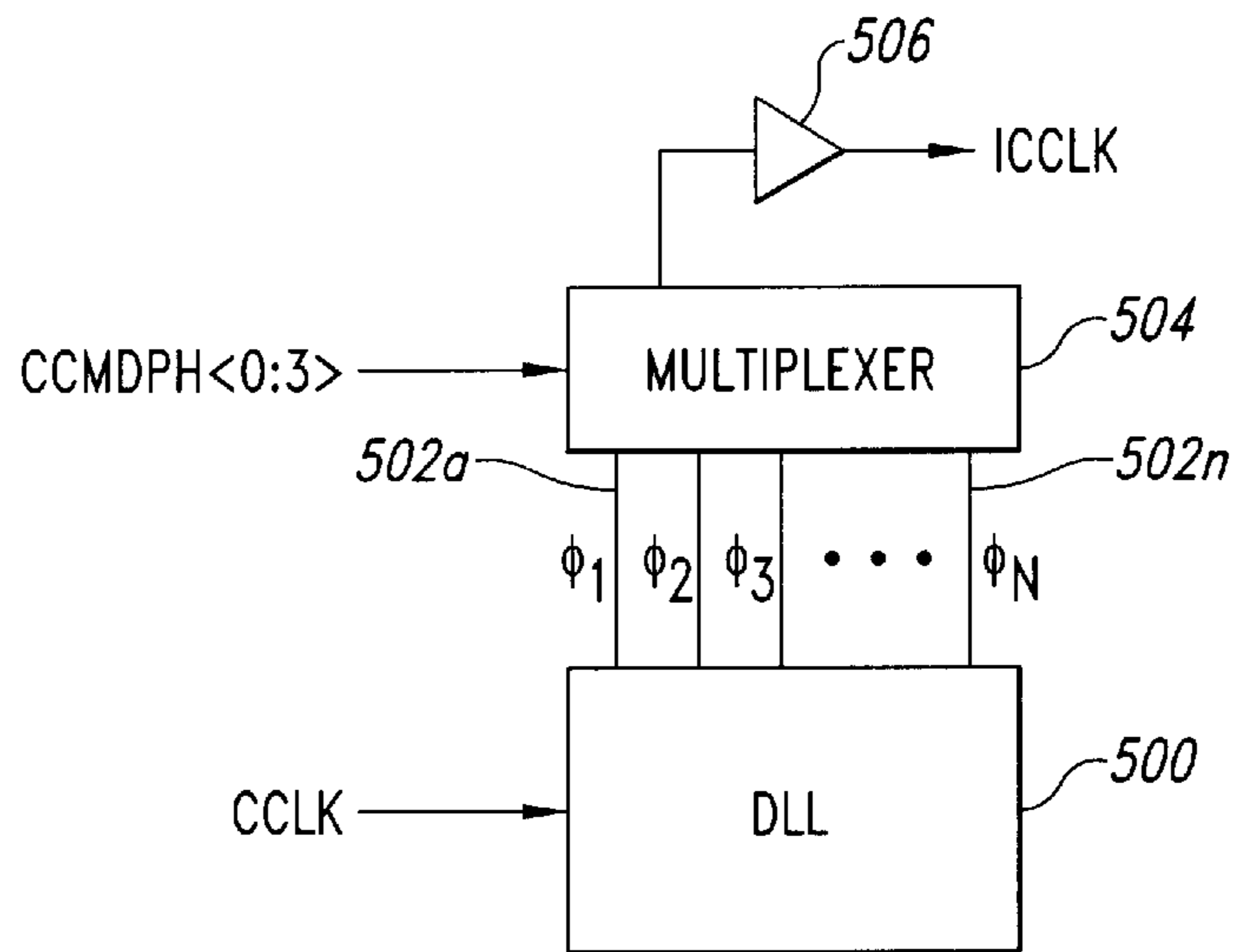


Fig. 12



2112

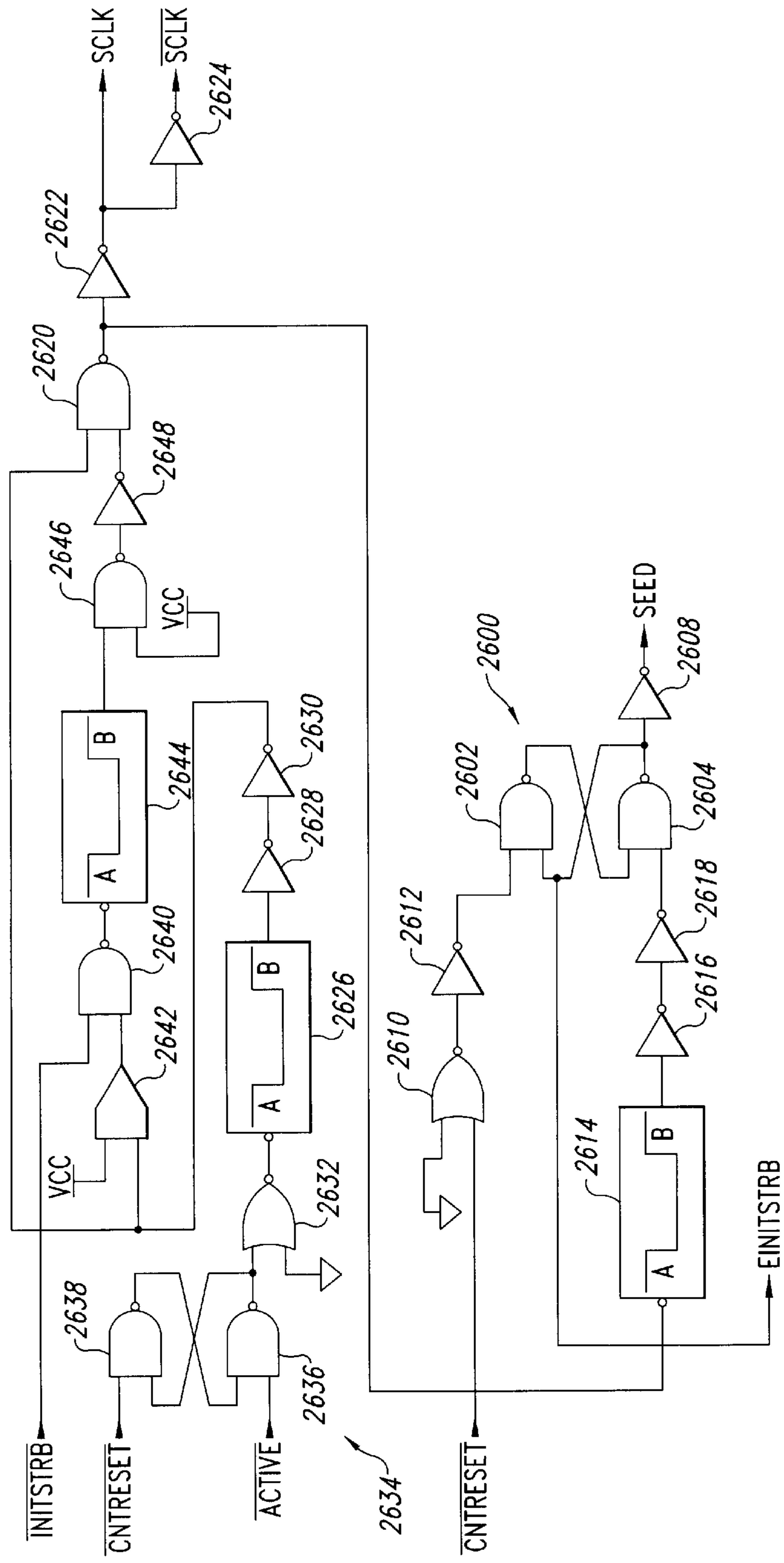


Fig. 11

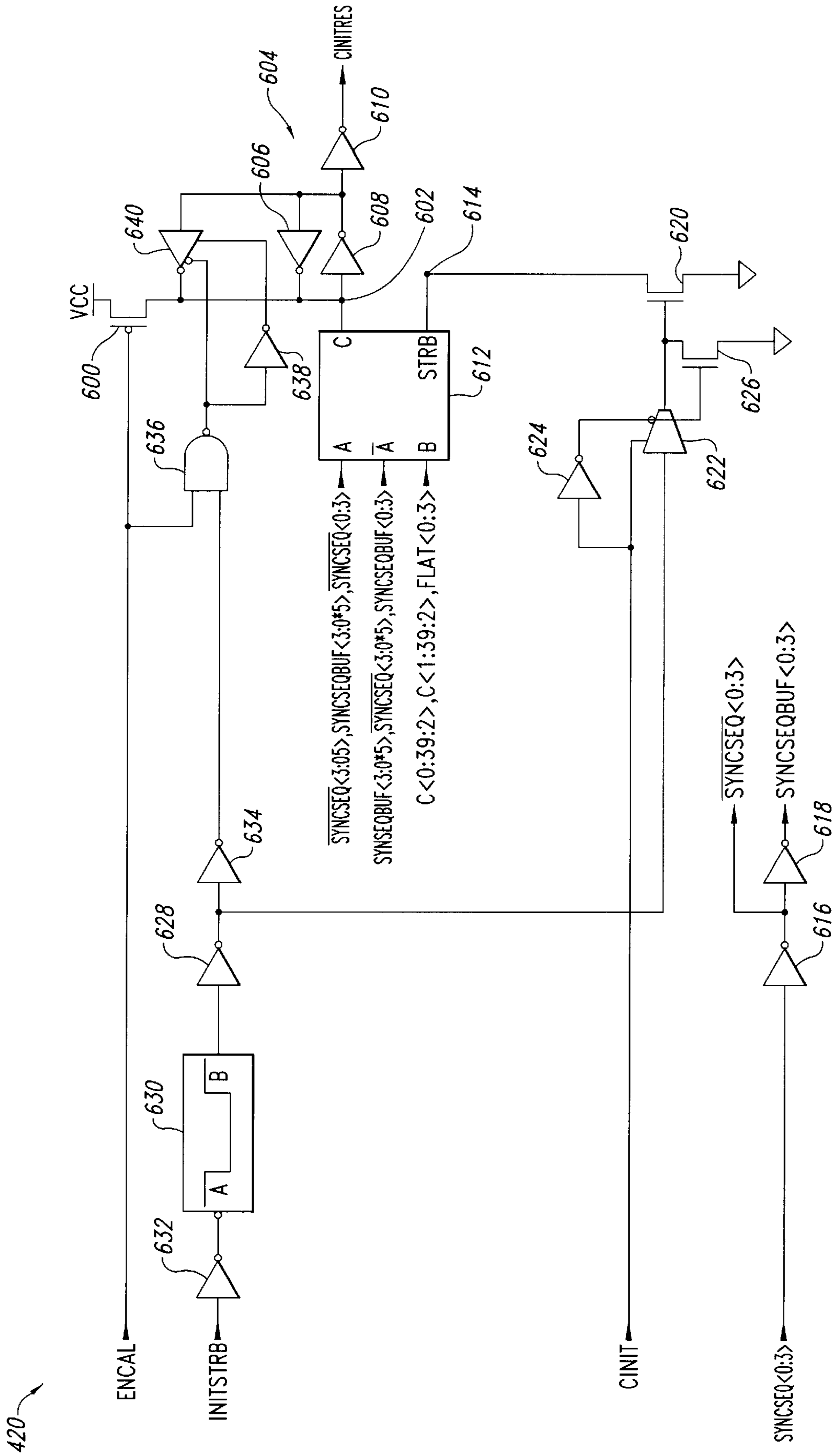


Fig. 13

612

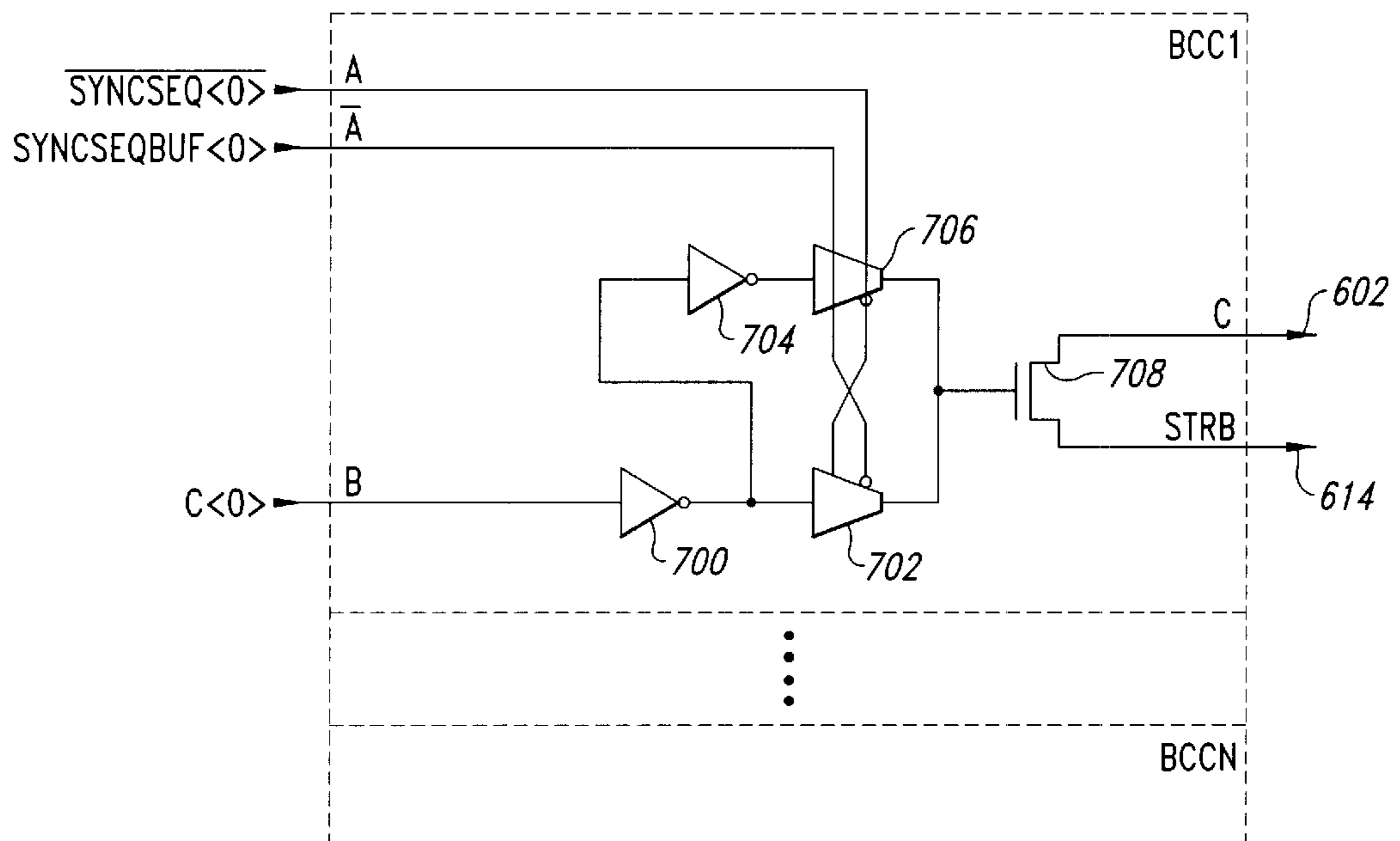


Fig. 14

446

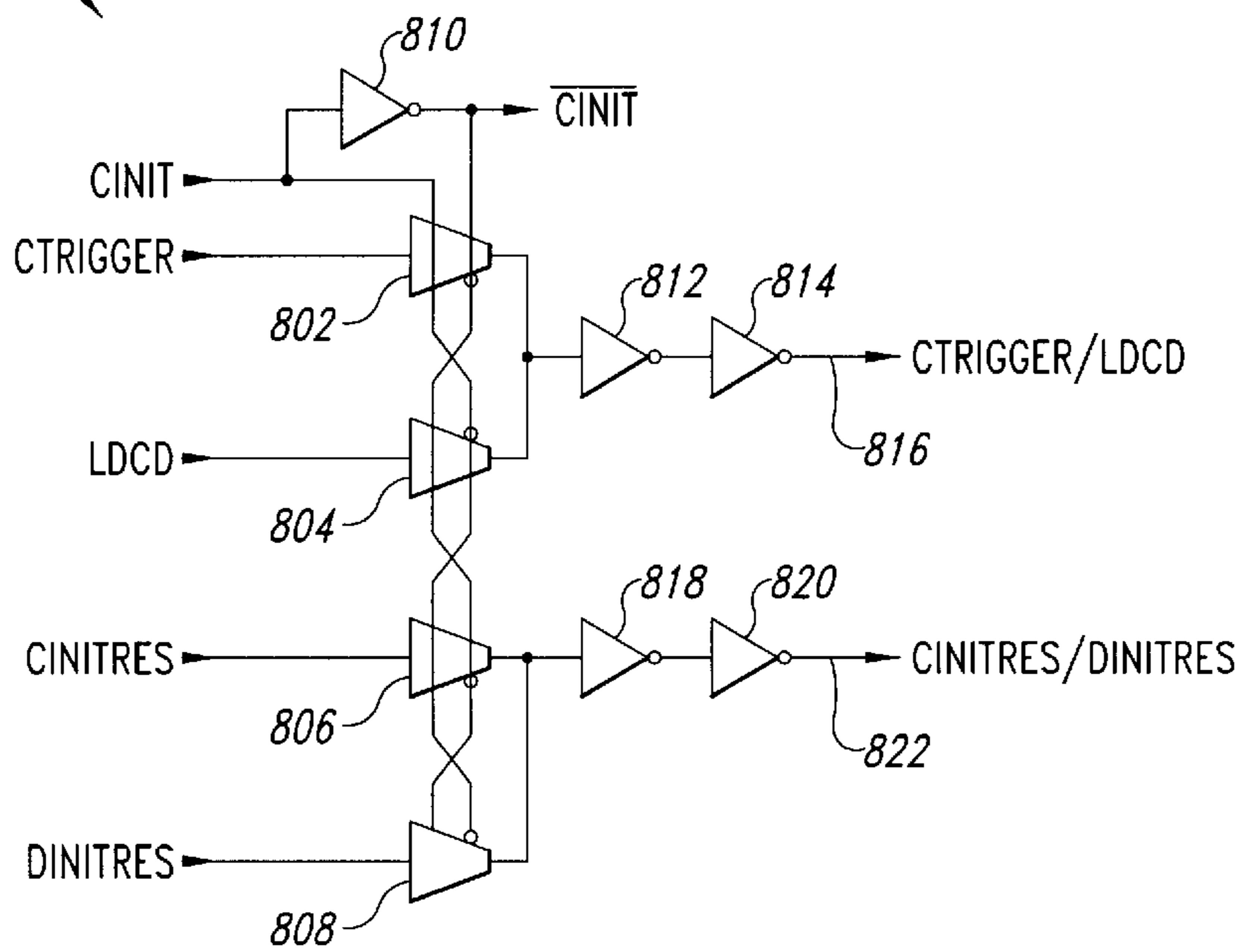


Fig. 15

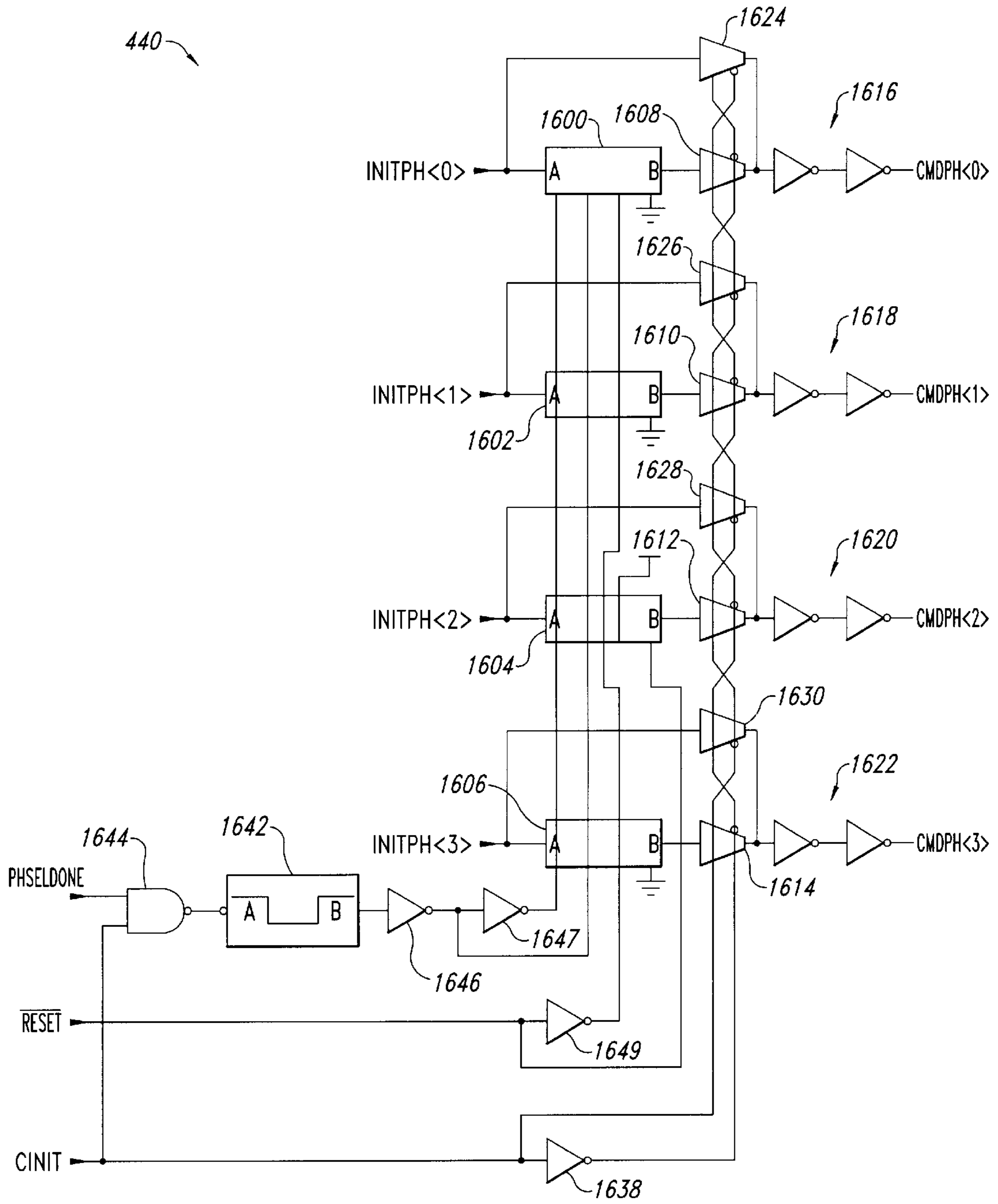


Fig. 16

**METHOD AND APPARATUS FOR  
RESYNCHRONIZING A PLURALITY OF  
CLOCK SIGNALS USED TO LATCH  
RESPECTIVE DIGITAL SIGNALS, AND  
MEMORY DEVICE USING SAME**

TECHNICAL FIELD

The present invention relates generally to integrated circuit devices, and more particularly to resynchronizing a plurality of internal clock signals derived from respective external clock signals to ensure the internal clock signals can be used in latching respective external digital signals at the optimum times.

BACKGROUND OF THE INVENTION

Conventional computer systems include a processor (not shown) coupled to a variety of memory devices, including read-only memories ("ROMs") which traditionally store instructions for the processor, and a system memory to which the processor may write data and from which the processor may read data. The processor may also communicate with an external cache memory, which is generally a static random access memory ("SRAM"). The processor also communicates with input devices, output devices, and data storage devices.

Processors generally operate at a relatively high speed. Processors such as the Pentium® and Pentium II® microprocessors are currently available that operate at clock speeds of at least 400 MHz. However, the remaining components of existing computer systems, with the exception of SRAM cache, are not capable of operating at the speed of the processor. For this reason, the system memory devices, as well as the input devices, output devices, and data storage devices, are not coupled directly to the processor bus. Instead, the system memory devices are generally coupled to the processor bus through a memory controller, bus bridge or similar device, and the input devices, output devices, and data storage devices are coupled to the processor bus through a bus bridge. The memory controller allows the system memory devices to operate at a lower clock frequency that is substantially lower than the clock frequency of the processor. Similarly, the bus bridge allows the input devices, output devices, and data storage devices to operate at a substantially lower frequency. Currently, for example, a processor having a 300 MHz clock frequency may be mounted on a mother board having a 66 MHz clock frequency for controlling the system memory devices and other components.

Access to system memory is a frequent operation for the processor. The time required for the processor, operating, for example, at 300 MHz, to read data from or write data to a system memory device operating at, for example, 66 MHz, greatly slows the rate at which the processor is able to accomplish its operations. Thus, much effort has been devoted to increasing the operating speed of system memory devices.

System memory devices are generally dynamic random access memories ("DRAMs"). Initially, DRAMs were asynchronous and thus did not operate at even the clock speed of the motherboard. In fact, access to asynchronous DRAMs often required that wait states be generated to halt the processor until the DRAM had completed a memory transfer. However, the operating speed of asynchronous DRAMs was successfully increased through such innovations as burst and page mode DRAMs which did not require that an address be provided to the DRAM for each memory access.

More recently, synchronous dynamic random access memories ("SDRAMs") have been developed to allow the pipelined transfer of data at the clock speed of the motherboard. However, even SDRAMs are incapable of operating at the clock speed of currently available processors. Thus, SDRAMs cannot be connected directly to the processor bus, but instead must interface with the processor bus through a memory controller, bus bridge, or similar device. The disparity between the operating speed of the processor and the operating speed of SDRAMs continues to limit the speed at which processors may complete operations requiring access to system memory.

A solution to this operating speed disparity has been proposed in the form of a computer architecture known as a synchronous link architecture. In the synchronous link architecture, the system memory may be coupled to the processor either directly through the processor bus or through a memory controller. Rather than requiring that separate address and control signals be provided to the system memory, synchronous link memory devices receive command packets that include both control and address information. The synchronous link memory device then outputs or receives data on a data bus that may be coupled directly to the data bus portion of the processor bus.

An example of a computer system **10** using the synchronous link architecture is shown in FIG. **1**. The computer system **10** includes a processor **12** having a processor bus **14** coupled through a memory controller **18** and system memory bus **22** to three packetized or synchronous link dynamic random access memory ("SLDRAM") devices **16a-c**. The computer system **10** also includes one or more input devices **20**, such as a keypad or a mouse, coupled to the processor **12** through a bus bridge **22** and an expansion bus **24**, such as an industry standard architecture ("ISA") bus or a peripheral component interconnect ("PCI") bus. The input devices **20** allow an operator or an electronic device to input data to the computer system **10**. One or more output devices **30** are coupled to the processor **12** to display or otherwise output data generated by the processor **12**. The output devices **30** are coupled to the processor **12** through the expansion bus **24**, bus bridge **22** and processor bus **14**. Examples of output devices **24** include printers and a video display units. One or more data storage devices **38** are coupled to the processor **12** through the processor bus **14**, bus bridge **22**, and expansion bus **24** to store data in or retrieve data from storage media (not shown). Examples of storage devices **38** and storage media include fixed disk drives floppy disk drives, tape cassettes and compact-disk read-only memory drives.

In operation, the processor **12** sends a data transfer command via the processor bus **14** to the memory controller **18**, which, in turn, communicates with the memory devices **16a-c** via the system memory bus **22** by sending the memory devices **16a-c** command packets that contain both control and address information. Data is coupled between the memory controller **18** and the memory devices **16a-c** through a data bus portion of the system memory bus **22**. During a read operation, data is transferred from the SLDRAMs **16a-c** over the memory bus **22** to the memory controller **18** which, in turn, transfers the data over the processor bus **14** to the processor **12**. The processor **12** transfers write data over the processor bus **14** to the memory controller **18** which, in turn, transfers the write data over the system memory bus **22** to the SLDRAMs **16a-c**. Although all the memory devices **16a-c** are coupled to the same conductors of the system memory bus **22**, only one memory device **16a-c** at a time reads or writes data, thus avoiding

bus contention on the memory bus 22. Bus contention is avoided by each of the memory devices 16a-c on the system memory 22 having a unique identifier, and the command packet contains an identifying code that selects only one of these components.

The computer system 10 also includes a number of other components and signal lines that have been omitted from FIG. 1 in the interests of brevity. For example, as explained below, the memory devices 16a-c also receive a master clock signal to provide internal timing signals, a data clock signal clocking data into and out of the memory device 16, and a FLAG signal signifying the start of a command packet.

A typical command packet CA<0:39> for an SLDRAM is shown in FIG. 2 and is formed by 4 packet words CA<0:9>, each of which contains 10 bits of data. As will be explained in more detail below, each packet word CA<0:9> is applied on a command address bus CA including 10 lines CA0-CA9. In FIG. 2, the four packet words CA<0:9> comprising a command packet CA<0:39> are designated PW1-PW4. The first packet word PW<sub>1</sub> contains 7 bits of data identifying the packetized DRAM 16a-c that is the intended recipient of the command packet. As explained below, each of the packetized DRAMs is provided with a unique ID code that is compared to the 7 ID bits in the first packet word PW<sub>1</sub>. Thus, although all of the packetized DRAMs 16a-c will receive the command packet, only the packetized DRAM 16a-c having an ID code that matches the 7 ID bits of the first packet word PW<sub>1</sub> will respond to the command packet.

The remaining 3 bits of the first packet word PW<sub>1</sub> as well as 3 bits of the second packet word PW<sub>2</sub> comprise a 6 bit command. Typical commands are read and write in a variety of modes, such as accesses to pages or banks of memory cells. The remaining 7 bits of the second packet word PW<sub>2</sub> and portions of the third and fourth packet words PW<sub>3</sub> and PW<sub>4</sub> comprise a 20 bit address specifying a bank, row and column address for a memory transfer or the start of a multiple bit memory transfer. In one embodiment, the 20-bit address is divided into 3 bits of bank address, 10 bits of row address, and 7 bits of column address. Although the command packet shown in FIG. 2 is composed of 4 packet words PW1-PW4 each containing up to 10 bits, it will be understood that a command packet may contain a lesser or greater number of packet words, and each packet word may contain a lesser or greater number of bits.

The memory device 16a is shown in block diagram form in FIG. 3. Each of the memory devices 16a-c includes a clock generator circuit 40 that receives a command clock signal CCLK and generates a large number of other clock and timing signals to control the timing of various operations in the memory device 16a. The memory device 16a also includes a command buffer 46 and an address capture circuit 48 which receive an internal clock signal ICLK, a command packet CA<0:9> on a 10 bit command-address bus CA, and a terminal 52 receiving a FLAG signal. A memory controller (not shown) or other device normally transmits the command packet CA<0:9> to the memory device 16a in synchronism with the command clock signal CCLK. As explained above, the command packet, which generally includes four 10-bit packet words PW1-PW4, contains control and address information for each memory transfer. The FLAG signal identifies the start of a command packet, and also signals the start of an initialization sequence. The command buffer 46 receives the command packet from the command-address bus CA, and compares at least a portion of the command packet to identifying data from an ID register 56 to determine if the command packet

is directed to the memory device 16a or some other memory device 16b, c. If the command buffer 46 determines that the command is directed to the memory device 16a, it then provides the command to a command decoder and sequencer 60. The command decoder and sequencer 60 generates a large number of internal control signals to control the operation of the memory device 16a during a memory transfer.

The address capture circuit 48 also receives the command packet from the command-address bus CA and outputs a 20-bit address corresponding to the address information in the command packet. The address is provided to an address sequencer 64, which generates a corresponding 3-bit bank address on bus 66, a 10-bit row address on bus 68, and a 7-bit column address on bus 70. The row and column addresses are processed by row and column address paths, as will be described in more detail below.

One of the problems of conventional DRAMs is their relatively low speed resulting from the time required to precharge and equilibrate circuitry in the DRAM array. The SLDRAM 16a shown in FIG. 3 largely avoids this problem by using a plurality of memory banks 80, in this case eight memory banks 80a-h. After a read from one bank 80a, the bank 80a can be precharged while the remaining banks 80b-h are being accessed. Each of the memory banks 80a-h receives a row address from a respective row latch/decoder/driver 82a-h. All of the row latch/decoder/drivers 82a-h receive the same row address from a predecoder 84 which, in turn, receives a row address from either a row address register 86 or a refresh counter 88 as determined by a multiplexer 90. However, only one of the row latch/decoder/drivers 82a-h is active at any one time as determined by bank control logic 94 as a function of a bank address from a bank address register 96.

The column address on bus 70 is applied to a column latch/decoder 100, which supplies I/O gating signals to an I/O gating circuit 4102. The I/O gating circuit 4102 interfaces with columns of the memory banks 80a-h through sense amplifiers 104. Data is coupled to or from the memory banks 80a-h through the sense amps 104 and I/O gating circuit 4102 to a data path subsystem 108 which includes a read data path 110 and a write data path 112. The read data path 110 includes a read latch 120 that stores data from the I/O gating circuit 4102. In the memory device 16a shown in FIG. 3, 64 bits of data are stored in the read latch 120. The read latch then provides four 16-bit data words to an output multiplexer 122 that sequentially supplies each of the 16-bit data words to a read FIFO buffer 124. Successive 16-bit data words are clocked into the read FIFO buffer 124 by a clock signal RCLK generated from the internal clock signal ICLK. The 16-bit data words are then clocked out of the read FIFO buffer 124 by a clock signal obtained by coupling the RCLK signal through a programmable delay circuit 126. The programmable delay circuit 126 is programmed during initialization of the memory device 16a so that the data from the memory device is received by a memory controller, processor, or other device (not shown in FIG. 3) at the proper time. The FIFO buffer 124 sequentially applies the 16-bit data words to a driver circuit 128 which, in turn, applies the 16-bit data words to a data bus DQ forming part of the processor bus 14 (see FIG. 1). The driver circuit 128 also applies one of two data clock signals DCLK0 and DCLK1 to respective data clock lines 132 and 133. The data clocks DCLK0 and DCLK1 enable a device, such as the processor 12, reading the data on the data bus DQ to be synchronized with the data. Particular bits in the command portion of the command packet CA0-CA9 determine which of the two

data clocks DCLK0 and DCLK1 is applied by the driver circuit 128. It should be noted that the data clocks DCLK0 and DCLK1 are differential clock signals, each including true and complementary signals, but for ease of explanation, only one signal for each clock is illustrated and described.

The write data path 112 includes a receiver buffer 140 coupled to the data bus 130. The receiver buffer 140 sequentially applies 16-bit data words from the data bus DQ to four input registers 142, each of which is selectively enabled by a signal from a clock generator circuit 144. The clock generator circuit 144 generates these enable signals responsive to the selected one of the data clock signals DCLK0 and DCLK1. The memory controller or processor determines which data clock DCLK0 or DCLK1 will be utilized during a write operation using the command portion of a command packet applied to the memory device 16a. As with the command clock signal CCLK and command packet, the memory controller or other device (not shown) normally transmits the data to the memory device 16a in synchronism with the selected one of the data clock signals DCLK0 and DCLK1. The clock generator 144 is programmed during initialization to adjust the timing of the clock signal applied to the input registers 142 relative to the selected one of the data clock signals DCLK0 and DCLK1 so that the input registers 142 can capture the write data at the proper times. In response to the selected data clock DCLK0 or DCLK1, the input registers 142 sequentially store four 16-bit data words and combine them into one 64-bit data word applied to a write FIFO buffer 148. The write FIFO buffer 148 is clocked by a signal from the clock generator 144 and an internal write clock WCLK to sequentially apply 64-bit write data to a write latch and driver 150. The write latch and driver 150 applies the 64-bit write data to one of the memory banks 80a-h through the I/O gating circuit 4102 and the sense amplifiers 104.

As mentioned above, an important goal of the synchronous link architecture is to allow data transfer between a processor and a memory device to occur at a significantly faster rate. However, as the rate of data transfer increases, it becomes more difficult to maintain synchronization between signals transmitted to the memory device 16a. For example, as mentioned above, the command packet CA<0:39> is normally transmitted to the memory device 16a in synchronism with the command clock signal CCLK, and the data is normally transmitted to the memory device 16a in synchronism with the selected one of the data clock signals DCLK0 and DCLK1. However, because of unequal signal delays and other factors, the command packet CA<0:39> may not arrive at the memory device 16a in synchronism with the command clock signal CCLK, and the data may not arrive at the memory device 16a in synchronism with the selected data clock signal DCLK0 or DCLK1. Moreover, even if these signals are actually coupled to the memory device 16a in synchronism with each other, they may lose synchronism once they are coupled to circuits within the memory device. For example, internal signals require time to propagate to various circuitry in the memory device 16a, differences in the lengths of signal routes can cause differences in the times at which signals reach the circuitry, and differences in capacitive loading of signal lines can also cause differences in the times at which signals reach the circuitry. These differences in arrival times can become significant at high speeds of operation and eventually limit the operating speed of memory devices.

The problems associated with varying arrival times are exacerbated as timing tolerances become more restricted with higher data transfer rates. For example, if the internal

clock ICLK derived from the command clock CCLK does not latch each of the packet words CA<0:9> comprising a command packet CA<0:39> at the proper time, errors in the operation of the memory device may result. Similarly, data errors may result if internal signals developed responsive to the data clocks DCLK0 and DCLK1 do not latch data applied on the data bus DQ at the proper time. Moreover, even if these respective clocks are initially synchronized, this synchronism may be lost over time during normal operation of the SDRAM 16a. Loss in synchronism may result from a variety of factors, including temperature variations in the environment in which the SDRAM 16a is operating, or drift in operating parameters of components within the SDRAM 16a. Thus, the command clock CCLK and data clocks DCLK0 and DCLK1 must occasionally be resynchronized to ensure synchronism is maintained.

One skilled in the art will understand that when synchronization of the clock signals CCLK, DCLK0, and DCLK1 is discussed, this means the adjusting of the timing of respective internal clock signals derived from these respective external clock signals so the internal clock signals can be used to latch corresponding digital signals at optimum times. For example, the command clock signal CCLK is synchronized when the timing of the internal clock signal ICLK relative to the command clock signal CCLK causes packet words CA<0:9> to be latched at the optimum time.

There is a need for maintaining synchronism between clock signals and the associated digital signals being latched responsive to such clock signals during normal operation of an SDRAM. Moreover, although the foregoing discussion is directed to synchronizing clock signals in SDRAMs, similar problems exist in other synchronous and asynchronous DRAMs, which must latch address, data, and control signals at increasingly high rates of speed.

#### SUMMARY OF THE INVENTION

According to one aspect of the present invention, the phases of a plurality of internal clock signals are adaptively adjusted where each respective internal clock signal causes a corresponding signal to be stored responsive to the respective internal clock signal. A system embodying the present invention may include a plurality of clock control circuits, each controlling the phase of a respective internal clock signal relative to a corresponding external clock signal in response to a respective phase command signal. At least one evaluation circuit is coupled to latches that are corresponding signals responsive to respective internal clock signals. Each evaluation circuit is adapted to receive a plurality of signals sequentially stored in the corresponding latch and generate a results signal indicating whether each of the signals has an expected value. A phase selector circuit operates in a storage mode to sequentially develop a plurality of phase command signals on an output and store corresponding result signals sequentially received on an input. The phase selector circuit further operates in an analysis mode to develop on the output a final phase command signal determined from the stored result signals.

A plurality of storage circuits are coupled to respective clock control circuits and to the output of the phase selector circuit. Each storage circuit stores the final phase command signal responsive to a corresponding clock domain signal. A clock-domain control circuit is adapted to receive a synchronization signal. When the synchronization signal is active, the clock-domain control circuit sequentially applies the result signals generated by respective evaluation circuits to the phase selector circuit and develops the clock domain

signals to store the resulting final phase command signals in the corresponding storage circuits. The clock-domain control circuit further operates when the synchronization signal goes inactive before final phase command signals have been determined for each internal clock signal to, when the synchronization signal again goes active, sequentially apply result signals such that final phase command signals are determined only for those internal clock signals not synchronized during the previous cycle of the synchronization signal.

#### BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is a block diagram of a conventional computer system using a plurality of SDRAM packetized memory devices.

FIG. 2 is diagram showing a typical command packet received by the SDRAMs of FIG. 1.

FIG. 3 is a block diagram of a conventional packetized DRAM used in the computer system of FIG. 1.

FIG. 4 is block diagram of a partial resynchronization circuit usable in each of the SDRAMs of FIG. 3 according to one embodiment of the present invention.

FIG. 5 is a schematic of the clock-domain control circuit of FIG. 4 according to one embodiment of the present invention.

FIG. 6 is a more detailed block diagram of one embodiment of the initialization sequencer of FIG. 4.

FIG. 7 is a schematic of one embodiment of the strobe generator of FIG. 6.

FIG. 8 is a schematic of one embodiment of the phase compare counter of FIG. 10.

FIG. 9 is a schematic of one embodiment of the compare control circuit of FIG. 6.

FIG. 10 is a schematic of one embodiment of the multiplexer of FIG. 6.

FIG. 11 is a schematic of one embodiment of the pattern generator clocking circuit of FIG. 6.

FIG. 12 is a more detailed block diagram of an embodiment of one of the variable-phase clock generation circuits of FIG. 4.

FIG. 13 is a more detailed block diagram of an embodiment of one of the evaluation circuits of FIG. 4.

FIG. 14 is a more detailed block diagram of one embodiment of the compare circuit of FIG. 13.

FIG. 15 is more detailed block diagram of an embodiment of the multiplexers of FIG. 4.

FIG. 16 is a detailed schematic of an embodiment of one of the phase select latches of FIG. 4.

#### DETAILED DESCRIPTION OF THE INVENTION

FIG. 4 is a schematic block diagram of a partial resynchronization circuit 410 according to one embodiment of the present invention. Typically, the partial resynchronization circuit 410 is contained in the command buffer 46 and the clock generation circuit 40 of the SDRAM 16a and synchronizes external clock signals CCLK, DCLK0, and DCLK1 during an initialization mode of the SDRAM 16a, as will be explained in more detail below. Components and signals that were previously described with reference to FIG. 3 have been given the same designations in FIG. 4, and will not be described in further detail.

The partial resynchronization circuit 410 includes three variable-phase clock generation circuits 418, 419, and 423,

(FIG. 4B) that generate internal clock signals ICLK, IDCLK0, and IDCLK1, respectively. The clock generation circuit 418, which is part of the clock generation circuit 40 of FIG. 3, generates the internal command clock signal ICLK in response to the command clock signal CCLK. The phase of the internal command clock signal ICLK relative to the command clock signal CCLK is controlled by a phase command CCMDPH<0:3> applied to the clock generation circuit 418. Similarly, the clock generation circuit 419 generates the internal data clock signal IDCLK0 having a phase relative to the data clock signal DCLK0 that is determined by a phase command DOCMDPH<0:3>, and the clock generation circuit 423 generates the clock signal IDCLK1 having a phase relative to the clock signal DCLK1 that is determined by a phase command DICMDPH<0:3>. During the initialization procedure, the resynchronization circuit 410 determines the optimum values for the phase commands CCMDPH<0:3>, DOCMDPH<0:3>, and DICMDPH<0:3>, as will be explained in more detail below.

The partial resynchronization circuit 410 includes command packet circuitry 411 (FIG. 4A) comprising a shift register 412 receiving command packets CA<0:39> applied on the command-address bus CA. The width of the command-address bus CA corresponds to the width of the shift register 412, and the number of packet words CA<0:9> in the command packet CA<0:39> corresponds to the number of stages of the shift register 412. In the embodiment of FIG. 4, the shift register 412 has four stages, each of which is 10 bits wide. Thus, the shift register 412 sequentially receives four 10-bit packet words CA<0:9>. Each of the four packet words CA<0:9> is shifted into the shift register 412, and from one shift register stage to the next, responsive to each transition of the internal clock signal ICLK. The shift register 412 also latches the FLAG signal applied on the flag line 52 coincident with each packet word CA<0:9>. Coincident with the start of each command packet CA<0:39> during normal operation of the memory device 16a, the FLAG signal transitions high for one-half of the period of the internal clock signal ICLK. The shift register 412 shifts high FLAG signal through each of the four stages of the shift register 412 responsive to each transition of the ICLK signal. During normal operation, the latched high FLAG signal is used to generate a plurality of control signals as it is shifted through stages of the shift register 412. Once four packet words CA<0:9>, which correspond to a single command packet CA<0:39>, are shifted into the shift register 412, the shift register generates a command trigger signal CTRIGGER. In response to the CTRIGGER signal, a storage register 414 loads the 44 bit contents of the shift register 412. In the embodiment shown in FIG. 4 in which four 10-bit packet words C<0:9> and 4 FLAG bits are shifted into the shift register 412, the storage register 414 receives and stores a 40-bit command word C<0:39>, and a 4 bit flag-latched word FLAT<0:3>. However, in the more general case, the shift register 412 has N+1 stages, each of which has a width of M bits, and the storage register 414 loads an M\*N bit command word. After the storage register 414 has been loaded, it continuously outputs the 40 bit command word C<0:39> and 4 bit flag-latched word FLAT<0:3>.

The initialization mode of the SDRAM 16a is signaled by a FLAG signal that is twice the width of the normal FLAG signal, i.e., a FLAG signal having a duration equal to the period of the ICLK signal. In response to the double-width FLAG signal, the shift register 412 activates a calibration signal CAL, causing the resynchronization circuit 410 to execute an initialization procedure to synchronize the CCLK, DCLK0, and DCLK1 clock signals, as will be



explained in more detail below. Thus, there will be at least two transitions of the ICLK signal during the initialization FLAG signal. During the initialization procedure, the shift register 412 once again generates the CTRIGGER signal after four packet words CA<0:9> are shifted into the shift register 412. In response to the active CTRIGGER signal, the storage register 414 again loads the latched command packet CA<0:39> and flag latched word FLAT<0:3>.

One embodiment of the shift register 412 that may be utilized in the resynchronization circuit 410 is described in more detail in U.S. patent application Ser. No. 08/994,461 to Manning, which is incorporated herein by reference. The detailed circuitry of the shift register 412 will not be discussed in further detail since such circuitry and operation is slightly tangential to the present invention. One skilled in the art will realize, however, the shift register 412 must be capable a latching packet words CA<0:9> received at very high rates during operation of the resynchronization circuit 410, and during normal operation of the memory device 16a containing the circuit 410. For example, in one embodiment the command clock CCLK has a frequency of 200 MHz, requiring the shift register circuit 412 to store one packet word CA<0:9> every 2.5 ns (i.e., one packet word in response to each falling and rising edge of the CCLK signal).

The partial resynchronization circuit 410 further includes an evaluation circuit 420 receiving the command word C<0:39> and the flag-latched word FLAT<0:3> from the storage register 414. The evaluation circuit 420 further receives an initialization strobe signal INITSTRB, enable calibration signal ENCAL, and synchronization sequence word SYNCSEQ<0:3> generated by an initialization sequencer 430 (FIG. 4B), and a command initialization signal CINIT developed by a clock-domain control circuit 422. As will be discussed in more detail below, the clock-domain control circuit 422 and initialization sequencer 430 generate a plurality of control signals to control operation of the resynchronization circuit 410. In response to the INITSTRB, ENCAL, and CINIT signals, the evaluation circuit 420 compares each bit of the captured command word C<0:39> and flag-latched word FLAT<0:3> to expected values determined by the SYNCSEQ<0:3> word and generates a command initialization results signal CINITRES in response to these comparisons. When the bits of the command word C<0:39> and flag-latched word FLAT<0:3> have their expected values, the evaluation circuit 20 drives the CINITRES signal high, indicating the command packet CA<0:39> and latched FLAG bits were successfully captured. In contrast, when at least one of the bits in the command word C<0:39> or flag-latched word FLAT<0:3> does not have its expected value, the evaluation circuit 420 drives the CINITRES signal inactive low, indicating the command packet CA<0:39> and latched FLAG bits were not successfully captured.

The partial resynchronization circuit 410 further includes data packet circuitry 424 (FIG. 4A) that operates in a manner analogous to the command packet circuitry 411 in capturing and evaluating data packet words D<0:15> applied on the data bus DQ. An input buffer 426 transfers data packet words D<0:15> received on the data bus DQ to the input registers 142, which latch the sequentially applied data packet words D<0:15> in response to a clock signal applied by a multiplexer 421. The multiplexer 421 applies either an internal data clock signal IDCLK0 or an internal data clock signal IDCLK1 to the input registers 142 in response to a select clock signal SELCLK generated by the time-domain control circuit 422 (FIG. 4B). The IDCLK0 and IDCLK1

clock signals are internal data clock signals generated by the variable-phase clock generation circuits 419 and 423, respectively, in response to the respective data clocks DCLK0 and DCLK1, as will be explained in more detail below. After four data packet words D<0:15> have been latched in the input registers 142, the write buffer 148 (FIG. 3) latches the four data packet words D<0:15> comprising the data packet in response to a load signal LDCD generated by the clock generator 144 (FIG. 3). In the embodiment of FIG. 4, each data word D<0:15> includes 16 bits, which is the width of the data bus DQ. Thus, the write buffer 148 stores and outputs 64 bits of data as a data word D<1:60> and a data word D0L<3:0>. The data word D0L<3:0> corresponds to the four bits of data sequentially latched on the DQ0 line of the data bus DQ, and the data word D<1:60> corresponds to the other 60 bits of data latched on the lines DQ1–DQ15 of the data bus DQ during the latching of the data packets. The data word D0L<3:0> is analogous to the flag-latched word FLAT<0:3>, and the function of both of these words will be described in more detail below.

An evaluation circuit 428 receives the D<1:60> and D0L<3:0> data words from the write buffer 148 and operates in a manner analogous to that previously described for the evaluation circuit 420 to compare these captured bits to expected data determined by the SYNCSEQ<0:3> word generated by the initialization sequencer 30. The evaluation circuit 28 develops a data initialization results signal DINITRES indicating whether each of the bits in the D<1:60> and D0L<3:0> words have their expected values. When the bits in the captured data words D<1:60> and D0L<3:0> all have their expected values, the evaluation circuit 428 activates the DINITRES signal, and deactivates this signal when any of these bits does not have its expected value. The evaluation circuit 428 receives the INITSTRB and ENCAL signals and SYNCSEQ<0:3> word from the initialization sequencer 430, and also receives an enable signal  $\overline{\text{ENABLE}}$  generated by a NOR gate 32 in response to D0INIT and D1INIT signals generated by the clock-domain control circuit 422. When either the D0INIT or D1INIT signals are active high, the NOR gate 432 drives the  $\overline{\text{ENABLE}}$  signal active low, which, in turn, activates the evaluation circuit 428.

A multiplexer 446 receives the CINITRES or DINITRES signals output by the evaluation circuits 420 and 428, respectively, and the CTRIGGER and LDCD signals. In response to the CINIT signal, the multiplexer 446 applies one of the CINITRES and DINITRES signals on a first output and one of the CTRIGGER or LDCD signals on a second output. When the CINIT signal is active high, the multiplexer 446 applies the CINITRES and CTRIGGER signals on its first and second outputs, respectively, if the CINIT signal is inactive low, the multiplexer 446 applies the DINITRES and LDCD signals on its respective first and second outputs.

An initialization phase selector 436 receives either the CINITRES or DINITRES signal output by the multiplexer 446. The initialization phase selector 436 further receives the CAL signal, a latch results signal LATRES, and a phase signal PHASEOK generated by the initialization sequencer 30. A multiplexer 438 applies either the ICLK signal generated by the variable-phase clock generation circuit 418 or the WCLK signal generated by the clock generator 40 (see FIG. 3) to clock the initialization phase selector 436. The multiplexer 438 applies the ICLK signal to clock the initialization phase selector 436 when the CINIT signal is

active high, and applies the WCLK signal when the CINIT signal is inactive low.

In response to these various signals, the initialization phase selector **436** develops an initialization phase word INITPH<0:3>, a phase select done signal PHSELDONE, and a phase ready signal PHREADY, which are applied to a number of components in the partial resynchronization circuit **410** as shown. This initialization phase word INITPH<0:3> is applied to the inputs of three phase select latches **440**, **442**, and **444** receiving the CINIT, D0INIT, and D1INIT signals, respectively. Each of the phase select latches **440–444** operates in either a transfer mode or a storage mode in response to the corresponding one of the CINIT, D0INIT, and D1INIT signals output by the clock-domain control circuit **422**. The phase select latches **440–444** each operate in the same way in response to the corresponding signals, and thus, for the sake of brevity, only the operation of the phase select latch **440** will now be described in more detail. The phase select latch **440** operates in the transfer mode when the CINIT signal is active high. In the transfer mode, the phase select latch **440** outputs the current value of the INITPH<0:3> word as the phase command CCMDPH<0:3> to the variable-phase clock generation circuit **418**, and latches the INITPH<0:3> word present on its input in response to the PHSELDONE signal going active high. When the CINIT signal goes inactive low, the phase select latch **440** operates in the storage mode, outputting the latched value of INITPH<0:3> word as the phase command CCMDPH<0:3> to the clock generation circuit **418**.

The operation of the initialization phase selector **436** in determining the optimum phase command CCMDPH<0:3>, DCMDPH<0:3>, or D1CMDPH<0:3> for the one of the clock signals CCLK, DCLK0, and DCLK1 being synchronized by the resynchronization circuit **410** will now be described in more detail before describing the overall operation of the resynchronization circuit **410**. One procedure that may be executed by the initialization phase selector **436** in determining each of these optimum phase commands is described in U.S. patent application Ser. No. 08/994,461 to Manning, which is incorporated herein by reference.

Briefly, according to this procedure, the initialization phase selector **436** operates in two modes in determining each optimum phase command, namely a load mode and an analysis mode. In the load mode, the initialization phase selector **436** sequentially increments the initialization phase word INITPH<0:3> to sequentially increment the phase of the one of the clock signals ICLK, D0CLK, or D1CLK being synchronized. For example, assume the CINIT signal is active high indicating the CCLK clock signal is being synchronized. When the CINIT signal is high, the phase select latch **440** applies INITPH<0:3> word as the phase command CCMDPH<0:3> to the clock generator **418**. In

this situation, as the initialization phase selector **436** sequentially increments the INITPH<0:3> word, the clock generation circuit **418** sequentially increments the phase of the ICLK signal. The shift register **412** attempts to accurately capture each initialization command packet responsive to the respective internal clock signals ICLK that sequentially vary in their timing relationship to the initialization command packets. During the load mode, the initialization phase selector **436** stores or load values for the CINITRES signal developed by the evaluation circuit **420** at corresponding phases of the ICLK signal. Recall, when a command packet is successfully captured the CINITRES signal has a binary “1” value, and otherwise is a binary “0.” The initialization phase selector **436** stores a value for the CINITRES signal at each value of the phase command CCMDPH<0:3>, and identifies which phase commands CMDPH<0:3> caused ICLK to clock the shift register **12** at the proper time to successfully capture these initialization command packets (i.e., which phase commands resulted in a binary 1 for the CINITRES signal).

In the analysis mode, the initialization phase selector **436** evaluates the stored values for the CINITRES signals at each value of the phase command CCMDPH<0:3>. More specifically, a single phase command CMDPH<0:3> that is most likely to be able to successfully capture packet words in an initialization command packet is selected from all the phase commands CCMDPH<0:3> that successfully captured the initialization command packets. This selected phase command CMDPH<0:3> is the command that is thereafter latched by the phase select latch **440** and applied to the clock generation circuit **418** to generate the ICLK signal during normal operation.

In operation, when the SLDRAM **16a** containing the partial resynchronization circuit **410** operates in the initialization mode, which is initiated by the FLAG signal going active high for one cycle of the ICLK signal, the partial resynchronization circuit **410** synchronizes the CCLK, DCLK0, and DCLK1 clock signals, as will now be explained in more detail. In synchronizing these clock signals, the partial resynchronization circuit **410** operates in two submodes, a power-up synchronization submode and a partial synchronization submode. The power-up synchronization submode is initiated by a reset signal RESET going active low, which typically occurs, for example, upon power-up of the computer system **10** (see FIG. 1) including the SLDRAM **16a**. In response to the low RESET signal, the clock-domain control circuit **422** drives the CINIT, D0INIT, D1INIT, and SO signals inactive low, and the memory controller (FIG. 1) applies a 15-bit repeating pseudo-random bit sequence on each line of the command-address bus CA, data bus DQ, and on line **52** receiving the FLAG signal. The 15-bit repeating pseudo-random synchronization bit sequence applied on these lines is shown in Table 1 below.

TABLE 1

FLAG	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0
CA<9>	0	0	0	0	1	0	1	0	0	1	1	0	1	1	1
CA<8>	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0
CA<7>	0	0	0	0	1	0	1	0	0	1	1	0	1	1	1
M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
CA<0>	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0
DQ<15>	0	0	0	0	1	0	1	0	0	1	1	0	1	1	1
DQ<14>	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0
M	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
DQ<0>	1	1	1	1	0	1	0	1	1	0	0	1	0	0	0

As seen from Table 1, the 15-bit pseudo-random bit sequence is complemented on adjacent lines of the command-address bus CA and data bus DQ. Thus, for example, the sequence starts with 0000 on line CA<9>, 1111 on CA<8>, 0000 on CA<7>, and so on such that the sequence applied on each line is the complement of the sequence applied on adjacent lines.

In response to the 15-bit pseudo-random bit sequence, the partial resynchronization circuit 410 places the SLDRAM 16a in the synchronization mode of operation. More specifically, as shown in Table 1, the pseudo-random bit sequence begins with consecutive 1's for the FLAG signal. As previously described, in response to two consecutive 1's latched for the FLAG signal, the shift register 12 activates the CAL signal to place the partial resynchronization circuit 410 in the initialization mode of operation.

When the CAL signal goes active high, the clock-domain control circuit 422 initially activates the CINIT signal and maintains the SO, D0INIT, and D1INIT signals inactive low. In response to the CINIT signal going active high, the multiplexer 446 applies the CINITRES signal to the initialization phase selector 436 and the CTRIGGER signal to the initialization sequencer 430. In addition, in response to the active high CINIT signal, the phase select latch 440 applies the initialization phase word INITPH<0:3> output by the initialization phase selector 436 as the phase command CCMDPH<0:3> to the variable-phase clock generation circuit 418. The multiplexer 38 applies the ICLK signal to clock the initialization phase selector 436 in response to the active CINIT signal.

When the CINIT signal is active, the partial resynchronization circuit 410 synchronizes the ICLK signal. To begin synchronizing the ICLK signal, the initialization phase selector 436 outputs an initialization phase word INITPH<0:3> through the phase select latch 440 as the phase command CCMDPH<0:3> to the variable-phase clock generation circuit 418. In response to the phase command CCMDPH<0:3>, the clock generation circuit 418 generates the ICLK signal having an initial phase relative to the CCLK signal that corresponds to the phase command CCMDPH<0:3>. The shift register 412 then latches four packet words CA<0:9> applied on the command-address bus CA in response to the ICLK signal. After four packet words CA<0:9> have been latched, the shift register 412 outputs the latched command word C<0:39> along with the flag-latched word FLAT<0:3> to the storage register 414 and generates the CTRIGGER pulse. In response to the CTRIGGER pulse, the storage register 414 latches and outputs the command word C<0:39> and flag-latched word FLAT<0:3>. The evaluation circuit 420 receives the latched C<0:39> and FLAT<0:3> words, and compares these words to expected values determined by the SYNCSEQ<0:3> word from the initialization sequencer 430. The initialization sequencer 430 generates the SYNCSEQ<0:3> word in response to the FLAT<0:3> word, as will be described in more detail below. The evaluation circuit 420 compares the latched command word C<0:39> and flag-latched word FLAT<0:3> to their expected values determined by the SYNCSEQ<0:3> word and activates the CINITRES signal when these words have their expected values. If any of the bits in the C<0:39> and FLAT<0:3> words does not have its expected value, the evaluation circuit 420 drives the CINITRES signal inactive, indicating the capture of these words at the current phase of the ICLK signal was unsuccessful.

The CINITRES signal is applied through the multiplexer 446 to the input of the initialization phase selector 436, which latches the value of the CINITRES signal in response

to the LATRES signal developed by the initialization sequencer 430. In the embodiment of FIG. 4, the initialization sequencer 430 pulses the LATRES signal once for every eight comparisons made by the evaluation circuit 420 as long as the CINITRES signal is active high. In this way, for a given phase of the ICLK signal, eight command packets CA<0:39> may be latched and subsequently compared by the evaluation circuit 420 to their corresponding expected values as long as the CINITRES signal remains active high. After the eighth comparison, the initialization sequencer 430 pulses the LATRES signal causing the initialization phase selector 436 to latch the CINITRES signal.

If any command packet CA<0:39> or flag-latched word FLAT<0:3> is latched unsuccessfully, however, the evaluation circuit 20 detects the error and drives the CINITRES signal inactive low. As soon as the CINITRES signal goes inactive low, the initialization sequencer 430 pulses the LATRES signal causing the initialization phase selector 436 to latch the low CINITRES signal. Thus, if all command packets are captured successfully, eight command packets will be captured at a given phase of the ICLK signal and a high CINITRES signal, indicating successful capture of the command packets, will be stored by the initialization phase selector 436. In contrast, if any one of the comparisons by the evaluation circuit 420 indicates the command packet was captured unsuccessfully, which is indicated by the CINITRES signal going low, comparisons at that phase of the ICLK signal are immediately terminated and the initialization phase selector 436 stores a low value for the CINITRES signal, indicating command packets were unsuccessfully captured at that particular phase of the ICLK signal.

As previously described, the initialization phase selector 436 latches the value of the CINITRES signal in response to the LATRES pulse. In addition, the initialization phase selector 436 also increments the value of the initialization phase word INITPH<0:3> in response to the pulsed LATRES signal. This new value of the INITPH<0:3> word is once again applied through the phase select latch 440 to the clock generation circuit 18 and corresponds to the new phase of the ICLK signal that is applied to the shift register 412 and used in latching packet words CA<0:9> applied on the command-address bus CA. Once again, the latched command packet CA<0:39> is applied to the evaluation circuit 420, which compares each bit of the latched command packet to an expected value determined by the SYNCSEQ<0:3> word. In response to this comparison, the evaluation circuit 20 once again develops the CINITRES signal having a value indicating whether the command packet CA<0:39> was successfully captured. The initialization phase selector 436 operates as previously described in latching a value for the CINITRES signal indicating whether command packets were successfully captured at the new phase of the ICLK signal. After latching a value for the CINITRES signal, the initialization phase selector 436 again increments the value of the INITPH<0:3> word which, once again, is applied through the phase select latch 440 as the phase command CCMDPH<0:3> to the clock generation circuit 418 which, in turn, generates the ICLK signal having a new phase relative to the ICLK signal. This process is repeated until the initialization phase selector 436 has stored a predetermined number of values for the CINITRES signal, each value corresponding to a different phase of the ICLK signal that was utilized in latching command packets CA<0:39> supplied on the command-address bus CA. In one embodiment, the initialization phase selector 436 latches 16 values of the CINITRES signal. In other words, 16 different phases of the ICLK signal are utilized to capture

command packets CA<0:39> applied on the command-address bus CA.

After the initialization phase selector 436 has stored 16 values for the CINITRES signal, the selector operates in the analysis mode to determine which of the 16 phases for the ICLK signal will be utilized to capture command packets CA<0:39> applied to the SDRAM 16a during normal operation. Recall, for each phase of the ICLK signal that successfully captured command packets CA<0:39>, the initialization phase selector 436 stored a binary 1 for the CINITRES signal. A binary 0 was stored for the CINITRES signal for all phases of the ICLK signal where the command packets were not successfully captured. Thus, the initialization phase selector 436 selects one of the phases for the ICLK signal that resulted in a binary 1 for the CINITRES signal. One process that may be utilized by the initialization phase selector 436 in determining the optimum phase for the ICLK signal is described in more detail in U.S. patent application Ser. No. 08/890,055 to Baker et al., which is incorporated herein by reference. After having determined the optimum phase for the ICLK signal, the initialization phase selector 436 outputs the initialization phase word INITPH<0:3> corresponding to this phase, and activates the PHSELDONE signal. In response to the active PHSELDONE signal, the phase select latch 440 latches the initialization phase word INITPH<0:3> corresponding to the optimum phase for the ICLK signal. The phase select latch 440 thereafter continuously outputs this value as the phase command word CCMDPH<0:3> to the clock generation circuit 418, which generates the ICLK signal having the corresponding phase. The phase select latch 440 actually does not output the latched initialization phase word INITPH<0:3> until the clock-domain control circuit 422 deactivates the CINIT signal, which occurs shortly after the phase selector 436 activates the PHSELDONE signal, as will be described in more detail below.

In response to the active PHSELDONE signal output by the initialization phase selector 436, the clock-domain control circuit 422 deactivates the CINIT signal, indicating an optimum phase for the ICLK signal has been determined and the synchronization of the CCLK signal is therefore completed. Coincident with deactivating the CINIT signal, the clock-domain control circuit 422 activates the D0INIT signal indicating the DCLK0 signal will now be synchronized. In response to the active D0INIT signal, the phase select latch 442 places the initialization phase word INITPH<0:3> output by the initialization phase selector 436 on its output as the phase command D0CMDPH<0:3> to the variable-phase clock generation circuit 419. In addition, when the CINIT signal goes inactive low, the multiplexer 446 applies the DINITRES signal to the initialization phase selector 436 and the LCD signal to clock the initialization sequencer 430. In addition, the multiplexer 438 applies the clock signal WCLK to clock the phase selector 436 in response to the low CINIT signal. When the D0INIT signal is active, the SELCLK signal goes active causing the multiplexer 421 to apply the clock signal IDCLK0 to clock the input registers 142, and in this way the IDCLK0 signal is utilized to capture data packets placed on the data bus DQ. The NOR gate 432 also activates the ENABLE signal in response to the active D0INIT signal to thereby enable the evaluation circuit 428.

The initialization phase selector 436 thereafter operates as previously described to latch 16 values for the DINITRES signal developed in response to corresponding phases of the IDCLK0 signal, and then determines the optimum value for the phase command D0CMDPH<0:3> to be applied to the variable-phase clock generation circuit 419. Once again,

after the initialization phase selector 436 has determined the optimum value for the D0CMDPH<0:3> word, the selector again generates the PHSELDONE pulse. In response to the PHSELDONE pulse, clock-domain control circuit 422 deactivates the D0INIT signal and activates the D1INIT signal, indicating synchronization of the IDCLK0 signal has been completed and synchronization of the IDCLK1 signal will now begin. It should be noted that the NOR gate 432 maintains the  $\overline{\text{ENABLE}}$  signal applied to the evaluation circuit 428 active in response to the active high D1INIT signal. The evaluation circuit 428 and initialization phase selector 436 thereafter operate identically to the manner previously described for synchronization of the IDCLK0 signal in determining the optimum phase command D1CMDPH<0:3> to be applied to the variable phase clock generation circuit 423 and thus, will not be described in further detail.

Once the initialization phase selector 436 has determined the optimum phase command D1CMDPH<0:3> to synchronize the IDCLK1 signal, the selector once again generates the PHSELDONE pulse. In response to the PHSELDONE pulse, the clock-domain control circuit 422 deactivates the D1INIT signal and activates the SO signal, indicating all three clock signals, ICLK, IDCLK0, and IDCLK1, have now been synchronized. The active high SO signal is typically applied as the SI signal to another SDRAM and enables initialization and synchronization of the next SDRAM to begin.

During the power-up submode of operation, the resynchronization circuit 410 synchronizes all three of the clock signals ICLK, IDCLK0, and IDCLK1. After this has been done, the clock-domain control circuit 422 operates in the partial synchronization submode. In the partial synchronization submode, the resynchronization circuit 410 synchronizes only those clock signals not synchronized during the previous active cycle of the CAL signal. The resynchronization circuit 410 enters the partial synchronization submode when the shift register 412 activates the CAL signal in response to the FLAG signal going high for one period of the ICLK signal. During the partial synchronization submode, the clock-domain control circuit 422 develops the CINIT, D0INIT, and D1INIT signals so that the clock signals ICLK, DCLK0, and DCLK1 may be partially synchronized during a single active cycle of the CAL signal, meaning less than all the clock signals may be synchronized during a given synchronization cycle, and only those clock signals not synchronized during the previous active cycle of the CAL signal are then synchronized during a subsequent synchronization cycle or cycles.

For example, assume the CAL signal goes active and the resynchronization circuit 410 begins synchronizing the clock signals ICLK, IDCLK0, and IDCLK1. Now assume that the CAL signal goes inactive low after the circuit 410 has synchronized the ICLK signal (i.e., after new phase command CCMDPH<0:3> for the ICLK signal has been determined), but before the DCLK0 signal has been synchronized (i.e., before the phase command D0CMDPH<0:3> has been determined). The next time the CAL signal goes active, placing the circuit 410 in the partial synchronization submode, the clock-domain control circuit 422 activates the D0INIT signal so that synchronization begins with the IDCLK0 signal. In other words, the ICLK signal is not again synchronized since it was successfully synchronized during the previous cycle.

This process continues during active cycles of the CAL signal until all three clock signals ICLK, IDCLK0, and IDCLK1 have been synchronized. At this point, during the

next active cycle of the CAL signal, the ICLK signal is again synchronized. The operation of the resynchronization circuit 410 in both the power-up and partial synchronization sub-modes will be discussed further below when the clock-domain control circuit 422 is described in more detail.

The overall operation of the partial resynchronization circuit 410 and general operation of several components within that circuit have now been described with reference to FIG. 4. At this point, several components of the partial resynchronization circuit 410 will now be described in more detail, along with exemplary embodiments of these components.

FIG. 5 is a schematic of the clock-domain control circuit 422 according to one embodiment of the present invention. As previously described, the clock-domain control circuit 422 sequentially activates the CINIT, D0INIT, and D1INIT signals in response to a number of signals to control synchronization of the three clock domains defined by the clock signals CCLK, DCLK0, and DCLK1, as will now be explained in more detail. The clock-domain control circuit 422 includes a NOR gate 2000 having its output coupled through series connected inverters 2002 and 2004 to develop the CINIT signal. The CAL signal is applied through an inverter 206 to a first input of the NOR gate 2000, and a register 2008 applies its output to a second input of the NOR gate 2000. When the CAL signal is active high and the output of the register 2008 is low, the NOR gate 2000 drives its output high which, in turn, drives the CINIT signal active high. The clock-domain control circuit 422 further includes registers 2010 and 2012, with the registers 2008–2012 having their inputs and outputs coupled in series between a supply voltage source  $V_{cc}$  and an input of an inverter 2018.

A NAND gate 2022 has its output coupled through an inverter 2023 to develop the D0INIT signal. The NAND gate 2022 receives the output of the register 2008 on a first input, the CAL signal on a second input, the output of a NAND gate 2014 on a third input, and the output of the register 2012 coupled through the inverter 2018 on a fourth input. If all these inputs are high, the NAND gate 2022 drives its output low and the inverter 2023, in turn, drives the D0INIT signal active high. The NAND gate 2014 has its output coupled through an inverter 2016 to develop the D1INIT signal in response to the output of the inverter 2018, the CAL signal, and the output of the register 2010 applied on respective inputs. When all these inputs are high, the NAND gate 2014 drives its output low causing the inverter 2016 to drive the D1INIT signal active high.

A pulse generator 2024 applies its output directly and through an inverter 2026 to clock the registers 2008–2012. The pulse generator 2024 receives the PHSELDONE signal on its input and generates a positive pulse of a fixed duration on its output in response to the falling-edge transition of the PHSELDONE signal. Recall, the PHSELDONE signal is generated by the initialization phase selector 436 (FIG. 4) whenever the phase selector has determined the optimum phase for the clock domain currently being synchronized. The registers 2008–2012 are reset in response to an output of a positive-edge delay circuit 2032. The registers 2008–2012 are conventional registers that drive their outputs low in response to the signals on their reset terminals going active low, and circuitry for implementing the function of these registers is well understood by those skilled in the art. A NAND gate 2028 applies its output through an inverter 2030 to the input of the positive-edge delay circuit 2032. The positive-edge delay circuit 2032 drives its output high a predetermined time after a positive edge transition on the output of the inverter 2030, and drives its output low without

such a delay in response to a falling-edge transition on the output of the inverter 2030. The NAND gate 2028 receives three inputs and whenever one or more of these inputs goes inactive low the NAND gate 2028 drives its output high resetting the registers 2008–2012. The positive-edge delay circuit 2032 ensures that the reset signal applied to the registers 2008–2012 stays active low for at least its delay time, even if the output of the NAND gate 2028 remains high for a shorter duration.

A NAND gate 2034 applies its output to one input of the NAND gate 2028, and receives the inverted CAL signal from the inverter 2006 on a first input and the output of the register 2012 on a second input. When the CAL signal is inactive low and the output of the register 2012 is high the NAND gate 2034 applies a low output to the NAND gate 2028 which, in turn, drives its output high resetting the registers 2008–2010. A NOR gate 2036 applies its output through an inverter 2038 to a second input of the NAND gate 2028. The NOR gate 2036 receives the CAL signal on a first input and a never calibrated signal  $\overline{NEVCAL}$  on a second input. The  $\overline{NEVCAL}$  signal is generated by an RS flip-flop 2004 including cross-coupled NAND gates 2042 and 2044. When both the CAL and  $\overline{NEVCAL}$  signals are low, the NOR gate 2036 drives its output high causing the inverter 2038 to apply a low signal to the NAND gate 2028 which, in turn, drives its output high resetting the registers 2008–2012. A NAND gate 2046 applies its output to an inverter 2048 which, in turn, applies an internal reset signal  $\overline{IRESET}$  to the final input of the NAND gate 2028. The NAND gate 2046 receives a reset signal  $\overline{RESET}$  and power up signal  $\overline{PWRUP}$  on respective inputs, and drives its output high when either of the signals goes active low. In response to the output of the NAND gate 2046 going high, the inverter 2048 drives the  $\overline{IRESET}$  signal active low causing the NAND gate 2028 to drive its output high, resetting the registers 2008–2012.

The clock-domain control circuit 422 further includes an inverter 2050 that develops the select output signal SO in response to the output from a NAND gate 2052. As mentioned above, the SO signal goes active high once all three clock domains CCLK, DCLK0, and DCLK1 have been successfully synchronized. The NAND gate 2052 receives the  $\overline{NEVCAL}$  signal on a first input, a select input signal SI on a second input, and the output from a NAND gate 2054 on a third input. When all of its inputs are high, the NAND gate 2052 applies a low output to the inverter 2050 which, in turn, activates the SO signal. The RS flip-flop 2040 develops the  $\overline{NEVCAL}$  signal in response to an output of a NAND gate 2056 applied on its set input and the  $\overline{IRESET}$  signal from the inverter 2048 applied on its reset input. When the  $\overline{IRESET}$  signal goes active low, which occurs when either or both of the  $\overline{RESET}$  or  $\overline{PWRUP}$  signals applied to the NAND gate 2046 go active low, the RS flip-flop 2040 latches the  $\overline{NEVCAL}$  signal active low. Conversely, the RS flip-flop 2040 latches the  $\overline{NEVCAL}$  signal inactive high to enable the NAND gate 2052 when the NAND gate 2056 drives its output low, which occurs when both the output of the register 2012 and the SI signal are high.

The NAND gate 2054 drives its output high, enabling the NAND gate 2052 when either of respective outputs from NAND gates 2058 and 2060 is low. The NAND gate 2058 is enabled by the CAL signal, and receives a current calibration done signal  $\overline{CCD}$  from an RS flip-flop 2062 including cross-coupled NAND gates 2064 and 2066. The RS flip-flop 2062 receives a set input from the NAND gate 2056, the  $\overline{IRESET}$  signal on a first reset input, and a second

reset input from a pulse generator 2068 and applied through an inverter 2070. The CAL signal is applied through an inverter 2072 to the input of the pulse generator 2068, which generates a positive pulse having a fixed duration in response to a falling-edge transition on the output of the inverter 2072. In operation, the RS flip-flop 2062 is reset, latching the CCD signal inactive low when either the CAL signal goes active high or the  $\overline{\text{IRESET}}$  signal goes active low. The RS flip-flop 2062 latches the CCD signal active high when the output of the NAND gate 2056 goes low.

The NAND gate 2060 receives the CAL signal applied through the inverter 2006 and the output of an RS flip-flop 2074 including cross-coupled NAND gates 2076 and 2078. An identification valid signal IDVALID is applied through an inverter 2080 to the set input of the RS flip-flop 2074, and the inverter 2048 applies the reset input to the RS flip-flop 2074. When the  $\overline{\text{IRESET}}$  signal goes active low, the RS flip-flop 2074 latches its output low, and thereafter, in response to an active high IDVALID signal, the inverter 2080 outputs an active low set input causing the RS flip-flop 2074 to latch its output high. The RS flip-flop 2074 maintains its output high until reset by the  $\overline{\text{INTRES}}$  signal going active low, which does not occur during normal operation of the clock-domain control circuit 422. Once the RS flip-flop 2074 has been set, this output enables the NAND gate 2060 which then drives its output low and high responsive to the CAL signal going low and high, respectively.

The overall operation of the clock-domain control circuit 422 will now be described in more detail. In operation, the clock-domain control circuit 422 operates in one of two modes, a reset mode and synchronization mode. The reset mode of operation is characterized by one or both of the  $\overline{\text{RESET}}$  and  $\overline{\text{PWRUP}}$  signals going active low which, in turn, drives the  $\overline{\text{IRESET}}$  signal active low. In addition, it is assumed that coincident with one or both of the  $\overline{\text{RESET}}$  and  $\overline{\text{PWRUP}}$  signals going active low, circuitry (not shown in FIG. 20) drives the CAL and IDVALID signals inactive low. In response to the  $\overline{\text{IRESET}}$  signal going low, the NAND gate 2028 drives its output high resetting the registers 2008–2012 such that each register drives its corresponding output low. In response to the respective low outputs from the registers 2008 and 2010, the NAND gates 2022 and 2014 drive their respective outputs high deactivating the D0INIT and D1INIT signals. Furthermore, in response to the low CAL signal, the NOR gate 2000 drives its output low deactivating the CINIT signal. In addition, the low  $\overline{\text{IRESET}}$  signal resets the RS flip-flops 2040, 2062, and 2074 which, in turn, disable the NAND gates 2052, 2058, and 2060 respectively. At this point, the disabled NAND gate 2052 drives its output high deactivating the SO signal. In summation, during the reset mode of operation, the clock-domain control circuit 422 resets the registers 2008–2012 and the RS flip-flops 2040, 2062, 2074, and also deactivates all of the CINIT, D0INIT, D1INIT, and SO signals.

During the synchronization mode, the clock-domain control circuit 422 sequentially activates the CINIT, D0INIT, and D1INIT signals in response to the PHSELDONE signal, and thereafter activates the SO signal once all three clock domains have been synchronized, as will now be explained in more detail. The clock-domain control circuit 422 operates in two submodes during the synchronization mode, an initial synchronization submode and a partial synchronization submode. The clock-domain control circuit 422 operates in the initial synchronization submode immediately after operation in the reset mode, and thereafter operates in the partial synchronization submode. After operating in the reset mode, the clock-domain control circuit 422 enters the

initial synchronization submode in response to circuitry (not shown in FIG. 20) in the SLDRAM 16a (FIG. 3) activating the CAL, SI and IDVALID signals. The high IDVALID signal sets the RS flip-flop 2074, enabling the NAND gate 2060. The high SI signal enables the NAND gate 2056 and also enables the NAND gate 2052 to operate responsive to the signals applied on its other two inputs. In response to the high CAL signal, the NOR gate 2000 drives its output high activating the CINIT signal. In addition, the high CAL signal enables a number of components within the clock-domain control circuit 422, and also causes the pulse generator 2068 to generate a pulse that resets the RS flip-flop 2062 if that flip-flop was previously set. During the initial synchronization submode, which by definition immediately follows the reset mode, this pulse generated by the pulse generator 2068 has no effect on the RS flip-flop 2062 since that flip-flop has just been reset during the reset mode. The generation of the pulse by the pulse generator 2068 in response to the CAL signal going high will be described in more detail below with reference to the partial synchronization submode of operation.

At this point, the clock-domain control circuit 422 applies the active high CINIT signal to a variety of components within the partial resynchronization circuit 410 (FIG. 4) and that circuit operates as previously described to synchronize the ICLK signal. As previously described with reference to FIG. 4, once the initialization phase selector 436 determines the optimum initialization phase word INITPH<0:3> to synchronize the ICLK signal, the initialization phase selector 436 pulses the PHSELDONE signal. In response to the falling edge of the PHSELDONE pulse, the pulse generator 2024 generates a pulse that clocks the registers 2008–2012, shifting the high signal applied on the input of the register 2008 to the output of that register. In response to the output of the register 2008 going high, the NOR gate 2000 drives its output low deactivating the CINIT signal. In addition, when the output of the register 2008 goes high, the NAND gate 2022, whose other three inputs were already high, drives its output low activating the D0INIT signal.

In response to the D0INIT signal going high, the partial resynchronization circuit 410 (FIG. 4) synchronizes the IDCLK0 signal as previously described. Once again, when the initialization phase selector 436 (FIG. 4) determines the optimum initialization phase word INITPH<0:3> to synchronize the IDCLK0 signal, the phase selector generates the PHSELDONE pulse. In response to the PHSELDONE pulse, the pulse generator 2024 once again clocks the registers 2008–2012, shifting the high on the input of the register 2010 to the output of that register. When the output of the register 2010 goes high, the NAND gate 2014, whose other two inputs are already high, drives its output low activating the D1INIT signal. Further in response to the output of the NAND gate 2014 going low, the NAND gate 2022 drives its output high deactivating the D0INIT signal. At this point, the partial resynchronization circuit 410 (FIG. 4) operates as previously described to synchronize the IDCLK1 signal and, once the signal has been synchronized, the initialization phase selector 436 (FIG. 4) applies the PHSELDONE pulse to the pulse generator 2024.

In response to the PHSELDONE pulse, the pulse generator 2024 once again clocks the registers 2008–2012, shifting the high on the output of the register 2010 to the output of the register 2012. In response to the output of the register 2012 going high, which indicates all three clock domains have now been synchronized, the inverter 2018 applies a low to the NAND gate 2014 which, in turn, drives its output high deactivating the D1INIT signal. Further in response to the

output of the register **2012** going high, the NAND gate **2056**, which now receives two high inputs, drives its output low causing the RS flip-flop **2040** to latch the  $\overline{\text{NEVCAL}}$  signal high and the RS flip-flop **2062** to latch the CCD signal high. In response to the CCD signal going high, the NAND gate **2058**, which now receives two high inputs, drives its output low causing the NAND gate **2054** to apply a high output to the NAND gate **2052**. At this point, all three inputs of the NAND gate **2052** are high, and the NAND gate **2052** accordingly drives its output low activating the SO signal which indicates all three clock domains have now been successfully synchronized.

The high output from the register **2012** also enables the NAND gate **2034** which, while the CAL signal remains active high, maintains its output high. When the CAL signal goes inactive low, the inverter **2006** drives its output high causing the NAND gate **2034** to drive its output low. In response to the output of the NAND gate **2034** going low, the NAND gate **2028** drives its output high, resetting the registers **2008–2012**, in anticipation of the next active cycle of the CAL signal.

The clock-domain control circuit **422** continues operating in the initial synchronization submode until successfully synchronizing all three clock domains during a single active cycle of the CAL signal, which may hereinafter be referred to as a synchronization cycle. During the initial synchronization submode, if the CAL signal goes inactive low before all three clock domains have been synchronized, the registers **2008–2012** are reset causing the clock-domain control circuit **422** to commence operation during the next active cycle of the CAL signal by again first activating the CINIT signal such that the partial resynchronization circuit **410** (FIG. 4) again starts by synchronizing the ICLK clock signal first. As a result, even if during a given active cycle of the CAL signal, both the ICLK and IDCLK0 have been successfully synchronized, if the CAL signal then goes inactive before synchronization of the IDCLK1 signal is complete, the clock-domain control circuit **422** nonetheless starts the next active cycle of the CAL signal by again synchronizing the ICLK signal.

This operation is understood by noting that the RS flip-flop **2040** latches the  $\overline{\text{NEVCAL}}$  signal active low until reset by a low output from the NAND gate **2056**, which occurs in response to a high output from the register **2012** indicating all three clock domains have been successfully synchronized. The  $\overline{\text{NEVCAL}}$  signal is applied to one input of the NOR gate **2036** and the CAL signal is applied to the other input of this NOR gate. Thus, when the CAL signal is active high, the NOR gate **2036** drives this output low, causing the inverter **2038** to apply a high signal to the NAND gate **2028**. When the CAL signal goes low before the RS flip-flop **2040** has set the  $\overline{\text{NEVCAL}}$  signal high, the NOR gate **2036** receives two low inputs once the CAL signal does go low. In response to these two low inputs, the NOR gate **2036** drives its output high causing the inverter **2038** to apply a low signal to the NAND gate **2028** which, in turn, drives its output high resetting the registers **2008–2012** as previously described. In other words, before the RS flip-flop **2040** is set to latch the  $\overline{\text{NEVCAL}}$  signal high, every time the CAL signal goes low, the NOR gate **2036** drives its output high which results in the registers **2008–2012** being reset.

Once all three clock domains ICLK, IDCLK0 and IDCLK1 have been successfully synchronized during the initial synchronization submode, the clock-domain control circuit **422** operates in the partial synchronization submode. During the partial synchronization submode, the clock-domain control circuit **422** synchronizes only those clock

domains not successfully synchronized during the previous active cycle or cycles of the CAL signal. For example, during the partial synchronization submode, if the ICLK clock domain was successfully synchronized and the partial resynchronization circuit **410** (FIG. 4) was in the process of synchronizing the IDCLK0 clock domain when the CAL signal goes inactive low, during the next active cycle of the CAL signal, the clock-domain control circuit **422** does not again synchronize the ICLK clock domain but instead starts by synchronizing the IDCLK0 clock domain. In this way, the clock-domain control circuit **422** does not unnecessarily resynchronize clock domains synchronized during previous active cycles of the CAL signal.

The operation of the clock-domain control circuit **422** during the partial synchronization submode will now be described in more detail. For the following description, it is assumed that the initial synchronization submode has just synchronized the three clock signals ICLK, IDCLK0 and IDCLK1 during the previous active cycle of the CAL signal. At this point, when the CAL signal goes active, the clock-domain control circuit **422** commences operation in the partial synchronization submode. If the CAL signal does not go inactive low before all of the three clock signals ICLK, IDCLK0 and IDCLK1 have been successfully synchronized, then the operation of the clock-domain control circuit **422** is identical to that previously described during the initial synchronization submode, except that the RS flip-flop **2040** has already latched the  $\overline{\text{NEVCAL}}$  signal inactive high. When the CAL signal goes low before all three clock domains have been synchronized, however, the registers **2008–2012** are not reset so that during the next active cycle of the CAL signal, the partial resynchronization circuit **410** (FIG. 4) begins synchronizing the clock domain that was in the process of being synchronized during the previous active cycle of the CAL signal but which was not successfully synchronized during that cycle. For example, assume that the CAL signal goes active, placing the clock-domain control circuit **422** in the partial synchronization submode. Further assume that the ICLK signal has been successfully synchronized and that the partial resynchronization circuit **410** is in the process of synchronizing the IDCLK0 signal. As previously described, when the IDCLK0 signal is being synchronized, the clock-domain control circuit **422** activates the D0INIT signal and deactivates the CINIT, D1INIT, and SO signals. At this point, the output of the register **2008** is high while the outputs of the registers **2010** and **2012** are low.

Now assume that while the partial resynchronization circuit **410** (FIG. 4) is synchronizing the IDCLK0 signal in response to the active high D0INIT signal, the CAL signal goes low before this synchronization is complete. In this situation, unlike the previous situations where either all three clock domains had been synchronized or the  $\overline{\text{NEVCAL}}$  signal was active low, the registers **2008–2012** are not reset in response to the low CAL signal, as will now be explained in more detail. Recall that the  $\overline{\text{NEVCAL}}$  signal is high, since all three clock domains were synchronized during the previous initial synchronization submode. The high  $\overline{\text{NEVCAL}}$  signal disables the NOR gate **2036** so that it maintains its output low when the CAL signal goes low. As a result, the inverter **2038** maintains its output high and does not, as previously described, go low causing the NAND gate **2028** to drive its output high to reset the registers **2008–2012**. In addition, the output of the register **2012** is at this point low, and this low output disables the NAND gate **2034**, which maintains its output high when the CAL signal goes low. Thus, during the partial synchronization submode, when the

CAL signal goes low, the registers 2008–2012 are not reset. In addition, note that the low CAL signal is also applied to the NAND gate 2022. In response to the low CAL signal, the NAND gate 2022 drives its output high deactivating the D0INIT signal which, in turn, disables synchronization of the IDCLK0 signal currently being executed by the partial resynchronization circuit 410 (FIG. 4). It should be noted that the CAL signal is applied directly to the NAND gates 2022 and 2014, and through the inverter 2006 to the NOR gate 2000, disabling all these gates when it is low. As a result, whichever one of the CINIT, D0INIT, and D1INIT signals is active when the CAL signal goes low, the associated one of these gates deactivates that signal in response to the low CAL signal.

At this point, assume the CAL signal again goes high signaling the start of another synchronization cycle. The high CAL signal enables the NAND gate 2022 which, because its three other inputs are still high as they were at the end of the previous synchronization cycle, drives its output low once again activating the D0INIT signal. In response to the D0INIT signal again going active high, the partial resynchronization circuit 410 (FIG. 4) once again begins synchronizing the IDCLK0 signal as previously described. With reference to FIG. 4, it should be noted that the initialization phase selector 436 also receives the CAL signal and resets itself in response to that signal going inactive low. Accordingly, the synchronization of the IDCLK0 starts over at the beginning and the initialization phase selector 436 must again store 16 DINITRES signals, each corresponding to a particular phase of the IDCLK0 signal, and thereafter select the optimum phase as previously described. In other words, if 8 of the required 16 samples of the DINITRES signal were stored when CAL went inactive low, these 8 values are discarded and the initialization phase selector 436 starts at the beginning and stores a new value for the first stored DINITRES signal.

The clock-domain control circuit 422 repeats this process as many times as required to synchronize all three of the clock domains ICLK, IDCLK0 and IDCLK1. Once all three clock domains have been synchronized, the registers 2008–2012 are reset as previously described so that during the next synchronization cycle, the clock-domain control circuit 422 activates the CINIT signal to again start by synchronizing the ICLK signal. Recall, that once all three clock domains have been synchronized, the register 2016 latches its output high enabling the NAND gate 2034 so that next time the CAL signal goes low, the NAND gate 2034 drives its output low causing the NAND gate 2028 to drive its output high which, in turn, resets the registers 2008–2012.

The partial synchronization submode of operation reduces the time required for the clock-domain control circuit 422 to synchronize all three clock domains when the synchronization cycle is interrupted before synchronization of all three domains is complete. Referring back to FIG. 1, this allows the memory controller 18 to synchronize the SLDRAMs 16a–16c, each containing the partial resynchronization circuit 410, while the computer system 10 is in operation. The memory controller 18 may initiate a synchronization cycle and thereafter, in response to, for example, a data request from the processor 12, may then terminate the synchronization cycle, retrieve the requested data, and transfer that data to the processor 12. Once that data transfer is complete, the memory controller 18 may once again initiate a synchronization cycle and the partial resynchronization circuits 410 in the SLDRAMs 16a–16c being synchronized thereafter synchronize only those clock domains not synchronized during the previous synchronization cycle.

The operation of the initialization sequencer 430 of FIG. 4 in controlling the partial resynchronization circuit 410 of FIG. 4 will now be described in more detail with reference to FIGS. 4 and 6. FIG. 6 is a more detailed functional block diagram of the initialization sequencer 430. The initialization sequencer 430 includes an initialization strobe generator 2100 that generates a plurality of control signals in response to either the CTRIGGER or LDCD signals output by the multiplexer 446. As previously described, the CTRIGGER pulse is generated after the four packet words CA<0:9> applied on the command-address bus CA have been latched and stored in the storage register 414 (FIG. 4), and the LDCD pulse is generated after four data packets DQ<0:15> applied on the data bus DQ have been latched. Furthermore, as previously described, the multiplexer 446 outputs the CTRIGGER signal when the ICLK signal is being synchronized and the LDCD pulse when either of the IDCLK0 or IDCLK1 signals is being synchronized.

A phase compare counter 2104 is clocked by the initialization strobe generator 2100 and develops a three bit phase compare count S<0:2> indicating the number of comparisons performed by the evaluation circuits 420, 428 (FIG. 4) at a given phase of the clock domain being synchronized. A compare control circuit 2106 receives the phase compare count S<0:2> and the one of the CINITRES or DINITRES signals corresponding to the clock domain currently being synchronized. In the following description, it is assumed to ICLK signal is being synchronized, so the CINITRES signal is applied to the compare control circuit 2106. In response to these applied signals, the compare control circuit 2106 applies the latched results pulse LATRES to the initialization phase selector 436 (FIG. 4), causing the initialization phase selector 436 to latch the value of the CINITRES signal. The compare control circuit 2106 generates the LATRES pulse when either the CINITRES signal is inactive low, or the count S<0:2> equals 111. Thus, the compare control circuit 2106 generates the LATRES pulse after eight successful comparisons at a given phase of the clock domain being synchronized, or when the CINITRES signal indicates an unsuccessful comparison. In addition, when either the count S<0:2> equals 111 or the CINITRES signal goes low, the compare control circuit 2106 deactivates the ENCAL signal applied to the evaluation circuits 420 and 428 (FIG. 4) to thereby reset these evaluation circuits in anticipation of evaluating packet words CA<0:9> captured at the next phase of the clock domain being synchronized. The compare control circuit 2106 also outputs the phase signal PHASEOK signal to the phase compare counter 2104 and initialization strobe generator 2100. The compare control circuit 2106 deactivates the PHASEOK signal when either the count S<0:2> equals 111 or the CINITRES signal goes low. In response to the PHASEOK signal going low, the phase compare counter 2104 resets the count S<0:2> to 000 and generates a count reset pulse  $\overline{\text{CNTREST}}$  indicating comparisons of packet words captured at a given phase of the clock domain being synchronized are complete. In addition, the low PHASEOK signal disables the initialization strobe generator 2100 until that signal again goes active high.

The initialization sequencer 430 further includes a pattern generator 2108 receiving either the flag-latched word FLAT<0:3> or latched word D0L<0:3> from a multiplexer 2110, and utilizes the applied word to develop the synchronization sequence word SYNCSEQ<0:3>. As previously described, the SYNCSEQ<0:3> word is applied to the evaluation circuits 420 and 428 (FIG. 4) to determine the expect data for these circuits. The multiplexer 2110 applies



the FLAT<0:3> word when the ICLK clock domain is being synchronized, and otherwise applies the DOL<0:3> word when either the IDCLK0 or IDCLK1 clock domains are being synchronized. A pattern generator clocking circuit 2112 clocks the pattern generator 2108 with a pair of complementary seed clock signals SCLK,  $\overline{\text{SCLK}}$ , and also applies a seed signal SEED to the pattern generator 2108. In response to these signals, the pattern generator 2108 utilizes the FLAT<0:3> or DOL<0:3> word output by the multiplexer 2110 to develop the synchronization sequence word SYNCSEQ<0:3> which, as previously described, is applied to the evaluation circuits 420 and 428 (FIG. 4) to determine expected data for these circuits. The pattern generator clocking circuit 2112 is controlled by the initialization strobe generator 2100 and reset in response to the  $\overline{\text{CNTRESET}}$  signal generated by the phase compare counter 2104.

The pattern generator 2108 may be a conventional pattern recognition circuit which, upon receiving the FLAT<0:3> or DOL<0:3> word equal to 1111, thereafter generates the predetermined sequence of values defined by the repeating 15 bit pseudo-random bit sequence applied on FLAG, CA, and DQ lines (see Table 1). In other words, the pseudo-random bit sequences starts with 1111 applied for the FLAG bit. The next four FLAG bits that are captured, one coincident with each packet word CA<0:9>, are 0101, followed by 1001, and so on as seen in Table 1. Thus, the pattern generator 2108 merely starts generating the expected values 0101, 1001, and so on for the SYNCSEQ<0:3> word after receiving the FLAT<0:3> or DOC<0:3> word equal to 1111. One skilled in the art will understand circuitry that may be utilized to develop the predetermined sequence of SYNCSEQ<0:3> words generated by the pattern generator 2108, such as a state machine formed from appropriate logic circuitry.

FIG. 7 is a more detailed schematic of one embodiment of the initialization strobe generator 2100 of FIG. 6. The initialization strobe generator 2100 includes a NAND gate 2200 that develops an active signal  $\overline{\text{ACTIVE}}$  on its output in response to either the CTRIGGER or LDCD signal applied on a first input. The PHASEOK signal enables the NAND gate 2200 when active high. A pulse generator 2202 generates a low output pulse having a predetermined duration in response to a falling-edge of the  $\overline{\text{ACTIVE}}$  signal. The output pulse of the pulse generator 2202 is applied through an inverter 2204 to develop a pulse trigger signal PTRIGGER. A NAND gate 2206 is enabled by an enable initialization strobe signal ENINITSTRB received on a first input, and receives the PTRIGGER signal on a second input. When enabled, the NAND gate 2206 outputs a complementary initialization strobe signal  $\overline{\text{INITSTRB}}$ , which is applied through an inverter 2208 to develop an initialization strobe signal INITSTRB. A pulse generator 2210 generates a negative pulse on its output in response to a falling-edge of the INITSTRB signal, and this output pulse is applied through a first inverter 2212 to develop a pulse initialization strobe signal PINITSRB and through a second inverter 2214 to develop a complementary pulse initialization strobe  $\overline{\text{PINITSTRB}}$ .

In operation, the initialization strobe generator 2100 is enabled when the PHASEOK and ENINITSTRB signals are active high. When enabled, the NAND gate 2200 drives the  $\overline{\text{ACTIVE}}$  signal active low in response to the CTRIGGER signal going active high. In response to the  $\overline{\text{ACTIVE}}$  signal going low, the pulse generator 2202 generates a low pulse on its output which is applied through the inverter 2204 to develop the PTRIGGER signal. In the embodiment of FIG. 7, the pulse generator 2202 generates a 2 nanosecond low

pulse so the PTRIGGER signal is accordingly a 2 nanosecond high pulse. In response to the high PTRIGGER pulse, the NAND gate 2206 pulses its output low and thereby develops the INITSTRB,  $\overline{\text{INITSTRB}}$  pulses. In response to the falling-edge of the INITSTRB pulse, the pulse generator 2210 generates a 1 nanosecond low pulse on its output which is applied through the inverters 2212 and 2214 to develop the PINITSTRB,  $\overline{\text{PINITSTRB}}$  pulses. Note that when the PHASEOK signal is inactive low, the NAND gate 2200 is disabled, driving the  $\overline{\text{ACTIVE}}$  and PTRIGGER inactive high and thereby inhibiting development of the INITSTRB,  $\overline{\text{INITSTRB}}$  and PINITSTRB,  $\overline{\text{PINITSTRB}}$  signals. Similarly, when the ENINITSTRB signal is inactive low, the NAND gate 2206 is disabled preventing development of the INITSTRB,  $\overline{\text{INITSTRB}}$  and PINITSTRB,  $\overline{\text{PINITSTRB}}$  signals.

FIG. 8 is a more detailed schematic of the phase compare counter 2104 of FIG. 6. The phase compare counter 2104 includes three registers 2300–2304 that develop the respective count bits S<0>, S<1>, and S<2>. A NOR gate 2306 has its output coupled directly and through an inverter 2308 to clock the registers 2300–2304 with complementary clock signals CLK,  $\overline{\text{CLK}}$ , which are generated in response to the  $\overline{\text{PINITSTRB}}$  pulse received on a first input of the NOR gate 2306. The NOR gate 2306 is enabled by a NAND gate 2310 receiving the CAL and PHASEOK signals on respective inputs. The output of the NAND gate 2310 is further applied through an inverter 2312 which develops a count reset signal  $\overline{\text{CNTRESET}}$  to reset the registers 2300–2304 when either or both of the CAL and PHASEOK signals go inactive low. The count bits S<0>–S<2> are fed back to the inputs of the respective registers 2300–2304 in order to cause the counter 2104 to increment its three bit binary count as it is clocked by the clock signals CLK,  $\overline{\text{CLK}}$ . Accordingly, the bit S<0> is fed back through an inverter 2304 to the input of the register 2300. An XOR gate 2316 receives the bits S<0> and S<1> on the respective inputs and applies its output to the input of the register 2302. An XOR gate 2318 applies its output to the input of the register 2304 in response to the S<2> bit applied on a first input and the logical AND of the S<0> and S<1> bits applied to a NAND gate 2320 an output through an inverter 2322 to the second input of the XOR gate 2318.

In operation, the phase compare counter 2104 operates in a conventional manner to increment the count S<0:2> from 000 to 111 as the registers 2300–2304 are clocked by the CLK,  $\overline{\text{CLK}}$  signals. During normal operation, the CAL and PHASEOK signals are active high, causing the NAND gate 2310 to enable the NOR gate 2306 and also causing the inverter 2312 to drive the  $\overline{\text{CNTRESET}}$  signal inactive high. At this point, the CLK,  $\overline{\text{CLK}}$  signals are generated in response to each  $\overline{\text{PINITSTRB}}$  pulse and thereby cause the registers 2300–2304 to increment the count S<0:2> from 000 to 111. If either the CAL or PHASEOK signals goes inactive low while the count S<0:2> is being developed, the NAND gate 2310 drives its output high, causing the inverter 2312 to drive the  $\overline{\text{CNTRESET}}$  signal active low resetting the count S<0:2> to 000. As previously described, the PHASEOK signal goes inactive low if a particular command or data packet was not successfully captured. Thus, the phase compare counter 2104 resets its count S<0:2> to 000 whenever a command or data packet is unsuccessfully captured, in anticipation of comparing 8 command or data packets captured at the next phase of the clock domain being synchronized.

FIG. 9 is a detailed schematic of one embodiment of the compare control circuit 2106 of FIG. 6. In the compare

control circuit 2106, a pulse generator 2400 generates a low output pulse in response to a falling-edge transition of either the CTRIGGER or LDCD signal, depending upon which of the clock domains is being synchronized. The output of the pulse generator 2400 is applied through an inverter 2402 to a NAND gate 2404 which is enabled by the PHREADY signal developed by the initialization phase selector 436 (FIG. 4). The PHREADY signal is developed by the initialization phase selector 436 to allow for settling time of the clock signal being synchronized after adjusting the phase of that clock signal, as will be understood by one skilled in the art. An RS flip-flop 2406 includes cross-coupled NAND gates 2408 and 2410 and receives the output of the NAND gate 2404 on a set input.

A NOR gate 2412 applies the reset input to the RS flip-flop 2406 in response to the output of an AND gate 2414 applied on a first input and the output of a NAND gate 2416 applied through an inverter 2418 to a second input. The AND gate 2414 receives the PINITSTRB signal on a first input and either the CINITRES or DINITRES signal applied through an inverter 2420 on a second input. When the output of the AND gate 2414 is high, the NOR gate 2412 drives its output low resetting the RS flip-flop 2406, which occurs when the PINITSTRB signal is high and the applied one of the CINITRES or DINITRES signals is inactive low. As previously discussed, when the applied one of the CINITRES or DINITRES signals is inactive low, a command or data packet has been unsuccessfully captured, and thus the RS flip-flop 2406 is reset in this situation. The NOR gate 2412 also drives its output low, resetting the RS flip-flop 2406, when the inverter 2418 drives its output high, which occurs when the NAND gate 2416 drives its output low. The NAND gate 2416 receives the PTRIGGER signal on one input and the count S<0:2> output by the phase compare counter 2104 (FIG. 23) on their respective inputs. When the count S<0:2> equals 111, and the PTRIGGER signal is high, the NAND gate 2416 drives its output low causing the inverter 2418 to drive its output high and the NOR gate 2412, in turn, to drive its output low resetting the RS flip-flop 2406.

The output of the RS flip-flop 2406 is applied through series connected inverters 2422, 2424 to generate the PHASEOK signal. The output of the inverter 2422 is further applied directly to one input of a NAND gate 2426 and indirectly through the delay and pulse generation circuitry 2425 to a second input of the NAND gate 2426. More specifically, the output of the inverter 2422 is input to a positive-edge delay circuit 2428 that develops a positive-edge transition on its output a predetermined time after receiving a positive-edge transition on its input. In response to a negative-edge transition on its input, the positive-edge delay circuit 2428 develops a negative-edge transition on its output without any such delay. The output of the positive-edge delay circuit 2428 is applied through an inverter 2430 to an input of a pulse generator 2432. The pulse generator 2432 operates as do previously described pulse generators, developing a low pulse on its output in response to a falling-edge transition on its input.

The output of the pulse generator 2432 is applied through three series connected inverters 2434–2438 to develop the latched results pulse LATRES. As explained above, the initialization phase selector 436 latches the value of either the CINITRES or DINITRES signal present on its input in response to the LATRES pulse. The LATRES pulse is also applied to one input of a positive-edge delay circuit 2440 having its other input coupled to the supply voltage  $V_{cc}$ . The positive-edge delay circuit 2440 develops a positive-edge

transition on its output a predetermined time after receiving a positive-edge transition of the LATRES pulse, and develops a negative-edge transition on its output without such delay in response to a negative-edge transition of the LATRES pulse. A NAND gate 2442 is enabled by the CAL signal on a first input and receives the output of a NAND gate 2426 on a second input. The output of a NAND gate 2442 is coupled through an inverter 2444 to develop the ENCAL signal which, as described above with reference to FIG. 4, enables the evaluation circuits 420 and 428 (FIG. 4) when active high, and resets these circuits when inactive low. When the CAL signal is active high, the NAND gate 2442 drives its output low, in response to the output of the NAND gate 2426 going high, and drives its output high in response to the output of the NAND gate 2426 going low.

The overall operation of the compare control circuit 2106 will now be described in more detail. In the following description, it will be assumed the compare control circuit 2106 receives the CTRIGGER and CINITRES signals, corresponding to the situation when the ICLK clock domain is being synchronized, as previously described above. When the PHREADY signal is active high, the falling edge of the CTRIGGER pulse generates a low output pulse causing the NAND gate 2404 to drive its output low which, in turn, resets the RS flip-flop 2406, thereby driving the output of the NAND gate 2408 high. In response to the high output of the NAND gate 2408, the PHASEOK signal goes active high, and the inverter 2422 applies a low output to the NAND gate 2426 which, in turn, drives its output high. At this point, the NAND gate 2442 receives two high inputs and drives its output low causing the inverter 2444 to activate the ENCAL signal. In addition, note that the low output of the inverter 2422 does not cause the pulse generator 2432 to generate a low pulse, but instead the pulse generator 2432 drives its output high resulting in the inverter 2438 driving the LATRES signal inactive low. The low LATRES signal is applied through the positive-edge delay circuit 2440 to the NAND gate 2426 which, at this point, receives two low inputs.

After the RS flip-flop 2406 has been set in response to the falling-edge of the CTRIGGER signal, the compare control circuit 2106 maintains the PHASEOK and ENCAL signals active high, and the LATRES signal inactive low. The compare control circuit 2106 maintains these signal values until one of two events resets the RS flip-flop 2406. The RS flip-flop 2406 is reset when the NOR gate 2412 drives its output low, which occurs when either the AND gate 2414 drives its output high or the NAND gate 2416 drives its output low. The AND gate 2414 drives its output high when the PINITSTRB signal is high and the CINITRES signal is low. As previously described, the CINITRES signal is low when the evaluation circuit 420 (FIG. 4) determines the bits in the captured command packet do not match their expected data, meaning the command packet was unsuccessfully captured. Thus, when a command packet is unsuccessfully captured, the resulting low CINITRES signal causes the AND gate 2414 to drive its output high, and the NOR gate 2412, in turn, to drive its output low resetting the RS flip-flop 2406.

When the RS flip-flop 2406 is reset, the NAND gate 2408 drives its output low causing the inverter 2424 to drive the PHASEOK signal inactive low. In response to the low output from the NAND gate 2408, the inverter 2422 applies a high input to the NAND gate 2426. At this point, the other input of the NAND gate 2426 remains low and thus the NAND gate 2422 maintains its output low causing the inverter 2444 to maintain the ENCAL signal active high.

When the output of the inverter 2422 goes high, the positive-edge delay circuit 2428 drives its output high after the predetermined delay time, which in one embodiment of a compare control circuit 2106 is 2 nanoseconds. In response to the output of the positive-edge delay circuit 2428 going high, the inverter 2430 drives its output low causing the pulse generator 2432 to output a low pulse, which has a duration of 3 nanoseconds in one embodiment of the compare control circuit 2106. In response to the low pulse generated by the pulse generator 2432, the inverter 2438 drives the LATRES signal active high causing the initialization phase selector 436 (FIG. 4) to latch the value of the CINITRES signal applied on its input, as previously described. When the LATRES signal goes active high, the positive-edge delay circuit 2440 drives its output high the predetermined time later, which is 0.5 nanoseconds in one embodiment of the compare control circuit 2106. At this point, the NAND gate 2426 receives two high inputs and drives its output low causing the NAND gate 2442 to drive its output high and the inverter 2444, in turn, to drive the ENCAL signal inactive low. As described above, when the ENCAL signal goes inactive low, the evaluation circuit 420 is reset in anticipation of comparing the next captured command packet to the associated expect data.

The second condition that resets the RS flip-flop 2406 occurs when the output of the NAND gate 2416 goes low causing the inverter 2418 to drive its output high and the NOR gate 2412, in turn, to drive its output low, resetting the RS flip-flop 2406. The NAND gate 2416 drives its output low when the PTRIGGER signal is active high, and the compare count S<0:2> developed by the phase compare counter (FIG. 21) equals 111. When this occurs, all inputs to the NAND gate 2416 are high, causing it to drive its output low and thereby reset the RS flip-flop 2406. Once reset, the compare control circuit 2106 operates as previously described to deactivate the PHASEOK and ENCAL signals and activate the LATRES signal. In sum, the PHASEOK and ENCAL signals are deactivated and the LATRES signal activated when either the compare count S<0:2> equals 111, or the CINITRES signal goes low.

FIG. 10 is a more detailed schematic of one embodiment of the multiplexer 2110 of FIG. 6. The multiplexer 2110 includes first and second pass gates 2500 and 2502 that operate in a complementary manner to apply either the latched FLAT<0:3> or DOL<3:0> word as a seed word A<0:3> to the pattern generator 2108 (FIG. 6). A NAND gate 2504 has its output applied directly and through an inverter 2506 to control the pass gate 2500, and a NAND gate 2508 has its output applied directly and through an inverter 2510 to control the pass gate 2502. The CINIT signal is applied directly to a first input of the NAND gate 2504, and is applied through an inverter 2512 to a first input of the NAND gate 2508. The NAND gates 2504 and 2508 are enabled by the CAL signal applied on respective second inputs.

In operation, when the CAL signal is inactive low, both NAND gates 2504 and 2508 drive their respective outputs high turning off pass gates 2500 and 2502 so that neither the FLAT<0:3> or DOL<3:0> words are output. When the CAL signal is active high, which of the FLAT<0:3> DOL<3:0> words are output as the seed word A<0:3> depends upon the state of the CINIT signal. When the CINIT signal is active high, the NAND gate 2504 drives its output low turning ON the pass gate 2500 which, in turn, outputs the FLAT<0:3> word as the seed word A<0:3>. In response to the high CINIT signal, the inverter 2512 drives its output low causing the NAND gate 2508 to drive its output high which, in turn, turns OFF the pass gate 2502.

When the CINIT signal is low, the NAND gate 2504 drives its output high turning OFF the pass gate 2500 and the NAND gate 2508 drives its output low turning ON the pass gate 2502 and thereby coupling the DOL<3:0> word to its output as the seed word A<0:3>. From the above description, recall that when the CINIT signal is active high, the ICLK clock domain is being synchronized, and when the CINIT signal is inactive low, either the IDCLK0 IDCLK1 clock domains are being synchronized. Thus, when the CINIT signal is active high during synchronization of the ICLK clock domain, the multiplexer 2110 outputs the FLAT<0:3> word as the seed word A<0:3> to the pattern generator 2108 (FIG. 6). If either the IDCLK0 or IDCLK1 clock domains are being synchronized, the multiplexer 2110 applies the DOL<3:0> word as the seed word A<0:3> to the pattern generator 2108.

FIG. 11 is a detailed schematic of one embodiment of the pattern generator clocking circuit 2112 of FIG. 6. The pattern generator clocking circuit 2112 includes an RS flip-flop 2600 comprising cross-coupled NAND gates 2602 and 2604 and having its output coupled through an inverter 2608 to develop the SEED signal. As previously explained, the SEED signal enables the pattern generator 2108 (FIG. 21) to store either the FLAT<0:3> or DOL<3:0> word output by the multiplexer 2110. A NOR gate 2610 has its output coupled through an inverter 2612 to apply a set input to the RS flip-flop 2600. The NOR gate 2610 has one input coupled to ground and receives the  $\overline{\text{CNTRESET}}$  signal on a second input. When the  $\overline{\text{CNTRESET}}$  signal goes active low, the NOR gate 2610 drives its output high and the inverter 2612 drives its output low, resetting the RS flip-flop 2600 which causes the NAND gate 2604 to drive its output low and the inverter 2608 to drive the SEED signal active high. A pulse generator 2614 generates a low output pulse that is applied through series connected inverters 2616 and 2618 to the reset input of the RS flip-flop 2600. The pulse generator 2614 receives its input from a NAND gate 2620 and generates the low pulse on its output in response to a falling-edge transition on the output of the NAND gate 2620. In response to the low pulse output by the pulse generator 2614, the inverter 2618 drives the reset input low, resetting the RS flip-flop 2600 and thereby causing the NAND gate 2604 to drive its output high and the inverter 2608 to drive the SEED signal inactive low. In addition, note that the output of the NAND gate 2602 develops the enable initialization strobe signal ENINITSTRB which, when high, enables circuitry in the initialization strobe generator 2100 (FIG. 6).

The pattern generator clocking circuit 2112 couples the output of the NAND gate 2620 through inverters 2622 and 2624 to develop the pair of complementary seed clock signals SCLK,  $\overline{\text{SCLK}}$  which, as previously described above, clock the pattern generator 2108 (FIG. 6) to generate sequential SYNCSEQ<0:3> words as it is clocked, each of the SYNCSEQ<0:3> words representing expect data corresponding to a particular captured command or data packet. A pulse generator 2626 applies a low output pulse through series connected inverters 2628 and 2630 to a first input of the NAND gate 2620. The pulse generator 2626 generates the low output pulse in response to a falling-edge transition from a NOR gate 2632. The NOR gate 2632 has one input coupled to ground and a second input coupled to the output of an RS flip-flop 2634 including cross-coupled NAND gates 2636 and 2638. The RS flip-flop 2634 receives the  $\overline{\text{ACTIVE}}$  signal on a set input and the  $\overline{\text{CNTREST}}$  signal on a reset input. In response to the  $\overline{\text{CNTREST}}$  signal going low, the RS flip-flop 2634 is reset, driving the output of the

NAND gate 2636 low which, in turn, causes the NOR gate 2632 to drive its output high. Once reset, the RS flip-flop 2634 is set in response to the  $\overline{\text{ACTIVE}}$  signal going active low, causing the NAND gate 2636 to drive its output high which, in turn, causes the NOR gate 2632 to drive its output low.

The pattern generator clocking circuit 2112 further includes a NAND gate 2640 receiving the  $\overline{\text{INITSTRB}}$  signal on a first input and an output from a positive-edge delay circuit 2642 on a second input. The positive-edge delay circuit 2642 has its input coupled to the output of the inverter 2630 and develops a positive-edge transition on its output a predetermined time after receiving a positive-edge transition on its input, and develops a falling-edge transition on its output in response to a falling-edge transition on its input without such delay. The output of the NAND gate 2640 is applied to an input of a pulse generator 2644 which develops a low output pulse in response to a falling-edge transition on its input. A NAND gate 2646 has one input coupled to the supply voltage  $V_{cc}$  and a second input coupled to the output of the pulse generator 2644. When the pulse generator 2644 develops the low pulse on its output, the NAND gate 2646 drives its output high, causing an inverter 2648 to apply a low signal on a second input of the NAND gate 2620. In contrast, when the output of the pulse generator 2644 is high, the NAND gate 2646 drives its output low, causing the inverter 2648 to apply a high output to the NAND gate 2620.

In operation, the pattern generator clocking circuit 2112 operates in two modes, a seed mode and an expect data generation mode. For the following description, assume the  $\overline{\text{CNTREST}}$  signal has just pulsed active low, resetting the RS flip-flop 2634 and RS flip-flop 2600. When the RS flip-flop 2600 is reset, the NAND gate 2604 drives its output low, causing the inverter 2608 to drive the SEED signal active high. When the RS flip-flop 2634 is reset, the NAND gate 2636 drives its output low, causing the NOR gate 2632 to drive its output high. At this point, the pulse generator 2626 maintains its output high and this high output is applied through the inverters 2628 and 2630 to the NAND gate 2620. In addition, the positive-edge delay circuit 2642 applies a high output to the NAND gate 2640 in response to the high output from the inverter 2630. At this point, the NAND gate 2640 receives two high inputs so its output is low, but it is assumed the pulse generator 2644 has already generated its low output pulse in response to the falling-edge transition from the NAND gate 2640. Thus, the pulse generator 2644 maintains its output high and the NAND gate 2646, in turn, drives its output low, causing the inverter 2648 to apply a high output to the NAND gate 2620. The NAND gate 2620 likewise also receives two high inputs at this point and accordingly drives its output low, causing the inverters 2622 and 2624 to drive the SCLK signal high and SCLK signal low, respectively.

The initialization strobe generator 2100 (FIG. 6) then drives the  $\overline{\text{ACTIVE}}$  and  $\overline{\text{INITSTRB}}$  signals active low. In response to the  $\overline{\text{INITSTRB}}$  signal going active low, the NAND gate 2640 drives its output high and the pulse generator 2644 maintains its output high in response to this positive-edge transition on its input. In response to the  $\overline{\text{ACTIVE}}$  signal going active low, the RS flip-flop 2634 is set, causing the NAND gate 2636 to drive its output high. In response to the high output from the NAND gate 2636, the NOR gate 2632 drives its output low, causing the pulse generator 2626 to generate a low pulse on its output. This low pulse output by the pulse generator 2626 is applied through the inverters 2628 and 2630 to the NAND gate 2620. In response to the low pulse from the inverter 2630,

the NAND gate 2620 drives its output high, causing the inverters 2622 and 2624 to clock the SCLK signal low and  $\overline{\text{SCLK}}$  high, respectively. Notice that also in response to the output of the inverter 2630 going low, the positive-edge delay circuit 2642 outputs a low to the NAND gate 2640, which already has a high output in response to the low  $\overline{\text{INITSTRB}}$  signal. At this point, when the low pulse output by the pulse generator 2626 terminates, the pulse generator again drives its output high and this high output is applied through the inverters 2628 and 2630 to the input of the NAND gate 2620. In response to the output from the inverter 2630 going high, the NAND gate 2620 again drives its output low, causing the inverters 2622 and 2624 to clock the SCLK signal high and  $\overline{\text{SCLK}}$  low, respectively. At this point, the pattern generator clocking circuit 2112 has generated a single SCLK,  $\overline{\text{SCLK}}$  clock pulse in response to the  $\overline{\text{ACTIVE}}$  signal setting the RS flip-flop 2634.

After the RS flip-flop 2634 has been set, the initialization strobe generator 2100 (FIG. 6) drives the  $\overline{\text{INITSTRB}}$  signal inactive high. In response to the  $\overline{\text{INITSTRB}}$  signal going active high, the NAND gate 2640, which now receives two high inputs, drives its output low. When the output of the NAND gate 2640 goes low, the pulse generator 2644 generates a low output pulse. In response to the low output pulse from the pulse generator 2644, the NAND gate 2646 drives its output high, causing the inverter 2648 to drive its output low. At this point, the NAND gate 2620 receives a high from the inverter 2630 and a low pulse from the inverter 2648 and accordingly drives its output high in response to the low output pulse from the inverter 2648. When the NAND gate 2620 drives its output high, the inverters 2622 and 2624 again drive the SCLK signal low and  $\overline{\text{SCLK}}$  high, respectively. Upon termination of the pulse generated by the pulse generator 2644, the NAND gate 2646 again drives its output low, causing the inverter 2648 to again apply a high output to the NAND gate 2620 which, in turn, now receives two high inputs and accordingly drives its output low. In response to the low output from the NAND gate 2620, the inverters 2622 and 2624 clock the SCLK signal high and the  $\overline{\text{SCLK}}$  low, respectively.

The pattern generator clocking circuit 2112 thereafter clocks the SCLK,  $\overline{\text{SCLK}}$  signals in response to pulses of the  $\overline{\text{INITSTRB}}$  signal. This is true because once the RS flip-flop 2634 is set by the  $\overline{\text{ACTIVE}}$  signal going active low, the pulse generator 2626 does not generate another pulse until the RS flip-flop 2634 is first reset by the  $\overline{\text{CNTREST}}$  signal and then again set by the  $\overline{\text{ACTIVE}}$  signal. Thus, the pulse generator 2626 generates a single pulse in response to the RS flip-flop 2634 being set. Thereafter, the NAND gate 2620 is enabled by the high output from the inverter 2630 and clocks the SCLK,  $\overline{\text{SCLK}}$  signals in response to each pulse generated by the pulse generator 2644. The pulse generator 2644 generates a pulse in response to each low transition output by the NAND gate 2640, which occurs when the low  $\overline{\text{INITSTRB}}$  terminates (i.e., when the  $\overline{\text{INITSTRB}}$  signal goes high).

FIG. 12 is a functional block diagram of one embodiment of the variable-phase clock generation circuit 418 of FIG. 4. Typically, the variable-phase clock generation circuits 418, 419, and 423 are identical, and thus, for the sake of brevity, only the clock generation circuit 418 will be described in more detail with reference to FIG. 12. The variable-phase clock generation circuit 418 includes a delay-locked loop 500 that develops a plurality of clock signals 502a-n in response to the CCLK signal. The clock signals 502a-n have phase shifts, designated  $\phi_1$ - $\phi_N$ , respectively, relative to the CCLK signal. In the embodiment of FIG. 12, the delay-locked loop 500 develops 16 clock signals 502a-n and

maintains a phase shift of  $180^\circ$  between the clock signals **502a** and **502n**. Thus, in this embodiment, the phases of the clock signals **502a-n** increase in increments of  $11.25^\circ$  from the phase  $\phi_1$  to  $\phi_{16}$ . In other words, the clock signal **502a** has a phase  $\phi_1$  relative to the CCLK signal, and each of the clock signals **502b-n** has a phase  $11.25^\circ$  greater than the preceding phase such that the clock signal **502n** has the phase  $\phi_{16}$  that is  $180^\circ$  greater than the phase  $\phi_1$ .

The clock signals **502a-n** are applied to respective inputs of a multiplexer **504** that also receives the phase command word **CCMDPH<0:3>**. In response to the phase command word **CCMDPH<0:3>**, the multiplexer **504** couples one of the clock signals **502a-n** to an output and through a buffer **506** to generate the ICCLK signal. The value of the phase command word **CCMDPH<0:3>** determines which of the clock signals **502a-n** is used to generate the ICCLK signal and thereby determines the phase of the ICCLK signal relative to the CCLK signal. A more detailed description of one embodiment of the variable-phase clock generation circuit **418** is described in the Baker patent application that was previously referenced, and which has been incorporated herein by such reference.

FIG. 13 illustrates one embodiment of the evaluation circuit **420** of FIG. 4, which, as previously described, compares the command word **C<0:39>** and flag-latched word **FLAT<0:3>** to expected values determined by the **SYNCSEQ<0:3>** word, and generates the CINITRES signal having a value indicating the result of this comparison. The evaluation circuit **420** includes a PMOS reset transistor **600** coupled between a supply voltage source  $V_{cc}$  and a sensing node **602** and receiving an enable calibration signal **ENCAL** on its gate. A latch **604** including two cross-coupled inverters **606**, **608** has its input coupled to the sensing node **602** and its output coupled to an input of an inverter **610** which develops the CINITRES signal on its output in response to the output of the latch **604**.

The evaluation circuit **420** further includes a compare circuit **612** coupled between the sensing node **602** and an enable node **614**. The compare circuit **612** receives the latched command word **C<0:39>** and flag-latched word **FLAT<0:3>** corresponding to the captured command packet received on the command-address bus **CA** and latched **FLAG** bits received on the flag line **52**, as previously described. In addition, the compare circuit **612** further receives a plurality of signals derived from the synchronization sequence word **SYNCSEQ<0:3>** generated by the initialization sequencer **430**. More specifically, each bit of the synchronization sequence word **SYNCSEQ<0:3>** is coupled through an inverter **616** to generate a complementary synchronization sequence word **SYNCSEQ<0:3>** which, in turn, is further coupled through an inverter **618** to generate a buffered synchronization sequence word **SYNCSEQBUF<0:3>**. The **SYNCHSEQ<0:3>** and **SYNCHSEQBUF<0:3>** words are utilized by the compare circuit **612** in determining whether each of the bits in the command word **C<0:39>** and latched **FLAG** word **FLAT<0:3>** has its expected value, as will be explained in more detail below.

The evaluation circuit **420** further includes an enable transistor **620** coupled between the enable node **614** and ground. An inverter **628** has its output applied through a transmission gate **622** to the gate of the enable transistor **620**. The CINIT signal is applied directly and through an inverter **624** to the control terminals of the transmission gate **622**. The output of the inverter **624** is further applied to a gate of a transistor **626** coupled between the gate of the enable transistor **620** and ground. When the CINIT signal goes active high, the inverter **624** drives its output low

turning OFF the transistor **626** and turning ON the transmission gate **622** and thereby coupling the output of the inverter **628** to the gate of the enable transistor **620**. Thus, when the CINIT signal is active high, the level at the output of the inverter **628** determines whether the enable transistor **620** turns ON or OFF. A pulse generator **630** provides a pulse signal to the input of the inverter **628** in response to the **INITSTRB** signal applied through an inverter **632** to its input. When the **INITSTRB** signal goes active high, the inverter **632** drives its output low causing the pulse generator **630** to apply a low pulse signal on the input of the inverter **628**, which, in turn, drives its output high for the duration of this pulse. This high output from the inverter **628** is coupled through the transmission gate **622**, when activated, turning ON the enable transistor **622**.

The output of the inverter **628** is further coupled through an inverter **634** to one input of a NAND gate **636** receiving the **ENCAL** signal on a second input. The output of the NAND gate **636** is applied directly and through an inverter **638** to enable terminals of a buffer **640** coupled between the output of the latch **604** and the sensing node **602** as shown. When the output of the NAND gate **636** goes low, the buffer **640** is enabled and applies the inverse of the signal on the output of the latch **604** on the sensing node **602**. If the output of the NAND gate **636** is high, the buffer **640** is disabled, placing its output in a high impedance state.

FIG. 14 is a more detailed schematic of the compare circuit **612** of FIG. 13 including a plurality of bit compare circuits **BCC1-BCCN**. There is one bit compare circuit **BCC1-BCCN** for each bit compared by the compare circuit **612**. In the embodiment of FIG. 6, the compare circuit **612** includes **44** bit compare circuit **BCC1-BCC44**, one for each bit of the command word **C<0:39>** and flag-latched word **FLAT<0:3>**. All the bit compare circuits **BCC1-BCCN** are identical, and thus, for the sake of brevity, only the bit compare circuit **BCC1** will be described in more detail. The bit compare circuit **BCC1** receives the bit **C<0>** of the command word **C<0:39>**, and applies this bit through a first inverter **700** to an input of a first transmission gate **702**, an through the first inverter **700** and a second inverter **704** to the input of a second transmission gate **706**. The transmission gates **702** and **706** receive the **SYNCSEQ<0>** and **SYNCSEQBUF<0>** signals on their respective control terminals as shown, and are activated in a complementary manner in response to the values of these signals. When the **SYNCSEQ<0>** signal is high and **SYNCSEQBUF<0>** signal is low, the transmission gate **702** turns ON and transmission gate **706** turns OFF, and when the signals **SYNCSEQ<0>** and **SYNCSEQBUF<0>** are low and high, respectively, the transmission gate **706** turns ON and transmission gate **702** turns OFF. The outputs of the transmission gates **702** and **706** are applied to a gate of a comparison transistor **708** coupled between the sensing node **602** and the enable node **614**.

In operation, the bit compare circuit **BCC1** compares the value of the bit **C<0>** to its expected value determined by the values of the bits **SYNCSEQ<0>** and **SYNCSEQBUF<0>** and activates the compare transistor **708** when the bit **C<0>** does not have its expected value, as will now be explained in more detail. The initialization sequencer **430** (see FIG. 4) determines an expected value for the command bit **C<0>** from the latched **FLAG** word **FLAT<0:3>** as previously mentioned, and as will be discussed in more detail below. When the expected value of the command bit **C<0>** is high, the **SYNCSEQ<0>** and **SYNCSEQBUF<0>** bits are driven high and low, respectively, turning ON transmission gate **702** and turning OFF transmission gate **706**. The command

bit C<0> is then applied through the inverter 700 and through the turned ON transmission gate 702 to the gate of the compare transistor 708. If the command bit C<0> is high as expected, the inverter 700 applies a low signal through the transmission gate 702 to the gate of the compare transistor 708, turning OFF this transistor. In contrast, if the command bit C<0> is a binary 0 instead of a binary 1 as expected, the inverter 700 drives its output high and this high output is applied through the transmission gate 702 to the gate of the transistor 708. In response to the high signal on its gate, the transistor 708 turns ON, coupling the sensing node 602 to the enable node 614.

When the expected value of the command bit C<0> is a binary 0, the  $\overline{\text{SYNCSEQ}}\langle 0 \rangle$  and  $\text{SYNCSEQBUF}\langle 0 \rangle$  are driven low and high, respectively, turning ON the transmission gate 706 and turning OFF the transmission gate 702. The command bit C<0> is then applied through the inverters 700 and 704 and through the turned ON transmission gate 706 to the gate of the compare transistor 708. If the command bit C<0> is a binary 0 as expected, the inverter 704 drives its output low, turning OFF the transistor 708 and isolating the sensing node 602 from the enable node 614. In contrast, if the command bit C<0> is not a binary 0 as expected but is instead a binary 1, the inverter 704 drives its output high, turning ON the transistor 708 which couples the sensing node 602 to the enable node 614.

Returning now to FIG. 13, the overall operation of the evaluation circuit 420 in comparing the value of each bit in the command word C<0:39> and flag-latched word FLAT<0:3> to its expected value will now be described in more detail. When the CINIT signal is inactive low, the transmission gate 622 turns OFF and the transistor 626 turns ON. The turned ON transistor 626 couples the gate of the enable transistor to ground, turning OFF the enable transistor 620 which isolates the enable node 614 from ground. In this situation, the evaluation circuit 420 is deactivated and does not evaluate the command word C<0:39> and flag-latched word FLAT<0:3>.

In operation, the evaluation circuit 420 is enabled when the CINIT signal is active high turning ON the transmission gate 622 and enable transistor 620, which couples the enable node 614 to approximately ground. The ENCAL signal goes inactive low before evaluation of a particular command word C<0:39> and flag-latched word FLAT<0:3>. In response to the low ENCAL signal, the transistor 600 turns ON, coupling the sensing node 602 to approximately the supply voltage  $V_{cc}$ . In response to the high on the sensing node 602, the latch 604 drives its output low and the inverter 610, in turn, drives the CINITRES signal on its output high. At this point, the INITSTRB signal is inactive low and the pulse generator 630 drives its output high causing the inverter 628 to drive its output low. The low output from the inverter 628 is applied through the turned ON transmission gate 622 to the gate of the enable transistor 620, turning OFF this transistor and thereby isolating the enable node 614 from ground.

In operation, before the evaluation circuit begins comparing latched command words C<0:39> and flag-latched words FLAT<0:3>, the ENCAL signal goes inactive low to reset the evaluation circuit 420 by turning ON the transistor 600 to drive the sensing node 602 to approximately the supply voltage  $V_{cc}$ . In response to the high voltage on the sensing node 602, the latch 604 drives its output low causing the inverter 610, in turn, to drive the CINITRES signal active high. It should be noted that when the ENCAL signal goes inactive low, the NAND gate 636 deactivates the buffer 640 enabling the transistor 600 to more easily drive the

sensing node 602 high. The ENCAL signal thereafter goes active high, enabling the evaluation circuit 420 to begin comparing latched command words C<0:39> and flag-latched words FLAT<0:3>. At this point, the synchronization sequence word SYNCSEQ<0:3> is applied to the evaluation circuit 420 and the corresponding  $\overline{\text{SYNCSEQ}}\langle 0:3 \rangle$  and  $\text{SYNCSEQBUF}\langle 0:3 \rangle$  words are, in turn, applied to the compare circuit 612, indicating the expected value for each of the bits in the latched C<0:39> and FLAT<0:3> words. At this point, the expected data in the form of the  $\overline{\text{SYNCSEQ}}\langle 0:3 \rangle$  and  $\text{SYNCSEQBUF}\langle 0:3 \rangle$  words and the latched data in the form of the C<0:39> and FLAT<0:3> words are applied to the compare circuit 612, but the compare circuit 612 is not yet enabled since the transistor 620 is turned OFF. The INITSTRB signal then goes active high and the pulse generator 630, in turn, generates the low pulse on its output, causing the inverter 628 to pulse its output high and thereby turn ON the enable transistor 620 so that the compare circuit 612 compares the latched command word C<0:39> and flag-latched word FLAT<0:3> to the expected data.

As previously described with reference to FIG. 14, when each bit of the command word C<0:39> and flag-latched word FLAT<0:3> has its expected value, the corresponding compare transistor 708 coupled between the sensing node 602 and enable node 614 does not turn ON. Thus, when the latched command words C<0:39> and FLAT<0:3> have their expected values, none of the transistors 708 in the compare circuit 612 turns ON and the sensing node 602 remains at approximately the supply voltage  $V_{cc}$ . Thus, when the words C<0:39> and FLAT<0:3> have their expected values, the voltage on the sensing node 602 remains high such that the latch 604 maintains its output low and the inverter 610 continues driving the CINITRES signal active high indicating the latched words C<0:39> and FLAT<0:3> were successfully captured. If any of the bits in the words C<0:39> and FLAT<0:3> does not have its expected value, the corresponding compare transistor 708 turns ON, coupling the sensing node 602 to approximately ground. When the sensing node 602 goes low, the latch 604 drives its output high causing the inverter 610 to drive the CINITRES signal low, indicating the C<0:39> and FLAT<0:3> words were not successfully captured.

It should be noted that the low pulse on the output of the pulse generator 630 results in the inverter 634 also pulsing its output low, which causes the NAND gate 636 to drive its output high for the duration of this pulse. As previously described, when the output of the NAND gate 636 goes high, the buffer 640 is disabled to enable the sensing node 602 to be more easily driven low if any of the bits were not successfully captured. After the end of the pulse generated by the pulse generator 630, the NAND gate 636 again drives its output low enabling the buffer 640 to drive the sensing node 602 to its desired value. As will be understood by one skilled in the art, the sensing node 602 may present a rather large capacitance due to all the components coupled in parallel to this node, and the buffer 640 includes transistors sized such that the buffer may drive this relatively large capacitance to its desired voltage and in this way assists the inverter 606 which typically has smaller sized transistors.

One embodiment of the multiplexer circuit 446 of FIG. 4 is illustrated in FIG. 15. The multiplexer 446 includes four transmission gates 802–808 receiving the CTRIGGER, LDCD, CINITRES, and DINITRES signals on their inputs, respectively. The CINIT signal is applied directly and through an inverter 810 to the control terminals of the transmission gates 802–808 as shown. In response to the

CINIT signal, the transmission gates **802** and **804** operate in a complementary manner to couple either the CTRIGGER or LDCD signal through a pair of series connected inverters **812** and **814** to an output terminal **816**. Similarly, the transmission gates **806** and **808** operate in a complementary manner in response to the CINIT signal, coupling either the CINITRES or DINITRES signal through series connected inverters **818** and **820** to an output terminal **822**. In operation, when the CINIT signal is active high, the multiplexer **446** outputs the CTRIGGER and CINITRES signals on the output terminals **816** and **822**, respectively. When the CINIT signal is inactive low, the multiplexer **446** outputs the LDCD and DINITRES signals on the terminals **816** and **822**, respectively. In this way, the multiplexer **446** applies the CTRIGGER pulse to clock the initialization sequencer **430** (FIG. 4) and the CINITRES signal to the phase selector **436** (FIG. 4) when the command clock signal CCLK is being synchronized (i.e., CINIT signal is high). In contrast, the multiplexer **446** applies the LDCD and DINITRES signals to the sequencer **430** and selector **436**, respectively, when either of the data clocks DCLK0 or DCLK1 is being synchronized (i.e., CINIT signal is low).

FIG. 16 is a more detailed schematic of the phase select latch **440** of FIG. 4. All the phase select latches **440–444** are identical, and thus, for the sake of brevity, only the latch **440** will be described in more detail with reference to FIG. 16. The INITPH<0:3> signals are applied to respective latch circuits **1600–1606**. The outputs of the latch circuits **1600–1606** are applied to respective pass gates **1608–1614** which are coupled to respective inverter pairs **1616–1622**. The latch circuits **1600–1606** may be selectively bypassed by respective pass gates **1624–1630**. The pass gates **1608–1614** and the pass gates **1624–1630** are connected to each other so that the pass gates **1608–1614** are enabled alternately with the pass gates **1624–1630** in response to the CINIT signal applied directly and through an inverter **1638** to the control terminals of these pass gates.

As explained earlier, in the storage mode during synchronization of the ICLK signal, the CINIT signal high, thereby enabling the pass gates **1624–1630** directly. As a result, the latches **1600–1606** are bypassed in the storage mode so that the phase command INITPH<0:3> is applied to the variable-phase clock generation circuit **418** (FIG. 4) to determine the phase of the ICLK signal relative to the CCLK signal. However, once the analysis mode has determined the optimum value for the phase command INITPH<0:3>, the PHSELDONE signal goes active high. The PHSELDONE signal is applied to one input of a NAND gate **1644**, which is enabled by the CINIT signal. In response to the active high PHSELDONE signal, the NAND gate **1644** drive its output low, thereby triggering a pulse generator **1642**. The pulse generated by the pulse generator **1642** is applied through an inverter **1646** to S inputs of the latch circuits **1600–1606**, and an inverter **1647** applies the complement of this signal to the S input of the latch circuits **1600–1606**. The latch circuits **1600–1606** then store the INITPH<0:3> signals that correspond to the optimum phase for the ICLK signal. When the CINIT signal goes low, which occurs a short time after the PHSELDONE signal goes active high, the INITPH<0:3> signals stored in the latch circuits **1600–1606** are then coupled through the inverter pairs **1616–1622** by the pass gates **1608–1614** and output as the phase command CCMDPH<0:3>. The latch circuits **1600–1606** store the CCMDPH<0:3> signals until either new CCMDPH<0:3> signals are stored in the latch circuits **1600–1606** during a synchronization cycle, or they are reset by the RESET signal applied to reset inputs of the latches **1600, 1602, and 1606**, and

through an inverter **1649** to the set input of the latch **1604**. By coupling the RESET signal in this way, the latches reset the stored INITPH<0:3> signals to 1101 when the RESET signal goes active low. As previously described, the stored CCMDPH<0:3> is applied to the clock generator **418** (FIG. 4) to thereby set the phase of the ICLK signal to an optimum value for use in capturing command packets applied on the command-address bus CA. A variety of different circuits may be utilized to perform the functions of the latches **1600–1606**, and such circuits are understood by one skilled in the art.

It is to be understood that even though various embodiments and advantages of the present invention have been set forth in the foregoing description, the above disclosure is illustrative only, and changes may be made in detail, and yet remain within the broad principles of the invention. Therefore, the present invention is to be limited only by the appended claims.

What is claimed is:

1. A method of synchronizing N clock signals applied to a packetized memory device, the method comprising:
  - placing the packetized memory device in a synchronization mode of operation;
  - synchronizing a portion of the N clock signals sequentially during the first synchronization mode of the packetized memory device;
  - placing the packetized memory device in a nonsynchronization mode of operation;
  - placing the packetized memory device in the synchronization mode of operation;
  - synchronizing only those of the N clock signals not synchronized during the prior synchronization mode; and
  - repeating the acts of placing the packetized memory device in a nonsynchronization mode of operation through synchronizing only those of the N clock signals not synchronized during the prior synchronization mode until all N clock signals have been synchronized.
2. The method of claim 1 wherein placing the packetized memory device in the synchronization mode comprises capturing a FLAG signal and generating a calibration signal when the FLAG signal has a predetermined binary value for two consecutive captures.
3. The method of claim 1 wherein the acts of synchronizing each of the N clock signals comprise:
  - repetitively applying digital signals having expected values to a latch;
  - storing the digital signals in the latch responsive to different respective phases of the clock signal being synchronized;
  - evaluating the digital signals stored in the latch to determine if the stored digital signals have the expected values;
  - identifying each phase of the clock signal being synchronized that caused the latch to store a digital signal having the expected value;
  - selecting a phase of the clock signal being synchronized that caused the latch to store digital signals having the expected values; and
  - adjusting the phase of the clock signal being synchronized to the selected phase.
4. A method of adaptively adjusting the phases of a plurality of internal clock signals relative to corresponding external clock signals, each internal clock signal triggering a latch to store a digital signal, the method comprising:

activating a synchronization signal to initiate a synchronization cycle;

repetitively applying digital signals to at least one of the latches;

storing the digital signals in one of the latches responsive to different respective phases of the corresponding internal clock signal;

evaluating the digital signals stored in the latch to determine if the stored digital signals have expected values;

identifying each phase of the corresponding internal clock signal that caused the latch to store digital signals having the expected values;

selecting a phase of the corresponding internal clock signal that caused the latch to store digital signals having the expected values;

adjusting the phase of the corresponding internal clock signal to the selected phase;

repeating the acts of repetitively applying digital signals to at least one of the latches to adjusting the phase of the corresponding internal clock signal to the selected phase for each of the internal clock signals until phases have been selected for all internal clock signals while the synchronization signal is active; and

repeating, when the synchronization signal goes inactive before phases for all internal clock signals have been selected, the acts of repetitively applying digital signals to at least one of the latches to adjusting the phase of the corresponding internal clock signal to the selected phase for all internal clock signals not having their phase selected during the previous active cycle of the synchronization signal until phases for all internal clock signals have been selected.

**5.** The method of claim **4** wherein evaluating the digital signals stored in the latch to determine if the stored digital signals have expected values comprises comparing the value of each digital signal to a constant predetermined value.

**6.** The method of claim **4** wherein repetitively applying digital signals to at least one of the latches comprises repetitively applying in parallel respective digital signals to the latches.

**7.** The method of claim **4** wherein evaluating the digital signals stored in the latch to determine if the stored digital signals have expected values comprises evaluating the digital signals stored in the latch a plurality of times for each phase of the internal clock signal and determining whether each time the digital signals have the expected values.

**8.** The method of claim **7** wherein identifying each phase of the corresponding internal clock signal that causes the latch to store digital signals having the expected values comprises identifying a phase of the internal clock signal as causing the latch to store digital signals having the expected values when the digital signals have the expected values all the plurality of times.

**9.** A method of adaptively adjusting the phases of a plurality of internal clock signals relative to corresponding external clock signals, each internal clock signal triggering a latch to store a digital signal, the method comprising:

activating a synchronization signal to initiate a synchronization cycle;

repetitively applying digital signals to at least one of the latches;

storing the digital signals in one of the latches responsive to different respective phases of the corresponding internal clock signal;

evaluating the digital signals stored in the latch to determine if the stored digital signals have expected values;

identifying each phase of the corresponding internal clock signal that caused the latch to store digital signals having the expected values;

selecting a phase of the corresponding internal clock signal that caused the latch to store digital signals having the expected values;

adjusting the phase of the corresponding internal clock signal to the selected phase;

repeating the acts of repetitively applying digital signals to at least one of the latches to adjusting the phase of the corresponding internal clock signal to the selected phase for each of the internal clock signals while the synchronization signal is active and until phases have been selected for all internal clock signals during a single active cycle of the synchronization signal; and

repeating during each active cycle of the synchronization signal after once selecting phases for all internal clock signals during a single active cycle of the synchronization signal, repetitively applying digital signals to at least one of the latches to adjusting the phase of the corresponding internal clock signal to the selected phase only for internal clock signals not having their phase selected during the previous active cycle of the synchronization signal until phases for all internal clock signals have been selected.

**10.** The method of claim **9** wherein evaluating the digital signals stored in the latch to determine if the stored digital signals have expected values comprises comparing the value of each digital signal to a constant predetermined value.

**11.** The method of claim **9** wherein repetitively applying digital signals to at least one of the latches comprises repetitively applying in parallel respective digital signals to the latches.

**12.** A system for adaptively adjusting the phases of a plurality of internal clock signals, each respective internal clock signal causing a corresponding latch to store a digital signal responsive to the respective internal clock signal, comprising:

a plurality of clock control circuits, each clock control circuit controlling the phase of a respective internal clock signal relative to a corresponding external clock signal responsive to a respective phase command signal;

a plurality of evaluation circuits coupled to respective latches, each evaluation circuit receiving a plurality of digital signals sequentially stored in the corresponding latch and generating a results signal indicating whether each of the digital signals has an expected value when a corresponding clock domain signal is active;

a phase selector circuit operating in a storage mode to sequentially develop a plurality of phase command signals on an output and store corresponding results signals sequentially received on an input, and operating in an analysis mode to develop on the output a final phase command signal from the stored results signals;

a plurality of storage circuits coupled to respective clock control circuits and to the output of the phase selector circuit, each storage circuit storing the final phase command signal responsive to a corresponding clock domain signal; and

a clock-domain control circuit receiving a synchronization signal and coupled to the evaluation, storage, and phase selector circuits, the clock-domain circuit developing a plurality of clock domain signals to control the evaluation, storage, and phase selector circuits to sequentially synchronize each internal clock signal by



storing a final phase command signal in the corresponding storage circuit, the clock-domain control circuit operable when the synchronization signal goes inactive before all internal clock signals have been synchronized to retain existing final phase command signals in the corresponding storage circuits, and to thereafter, when the synchronization signal again goes active, synchronize only those clock domains not synchronized during the previous cycle of the synchronization signal.

**13.** The system of claim **12** wherein the clock-domain control circuit further operates after the occurrence of a predetermined condition of the system to first determine final phase command signals for all internal clock signals during an active cycle of the synchronization signal until all clock signals are synchronized during a given cycle, and thereafter operates to determine final phase command signals only for those internal clock signals not synchronized during the previous active of the synchronization signal.

**14.** The system of claim **13** wherein the predetermined condition includes a reset signal going active.

**15.** The system of claim **12** wherein the clock-domain control circuit comprises:

- a pulse terminal receiving a pulse signal;
- a first reset circuit having inputs receiving at least one external reset signal and developing on an output an active clock-domain reset signal when any of the at least one external reset signal goes active;
- a shift register having an input coupled to a first voltage, N outputs, a clock terminal coupled to the pulse terminal, and a reset terminal, the shift register developing shift signals on respective outputs responsive to the pulse signal and resetting all shift signals responsive to the reset signal;
- a logic circuit including an enable terminal receiving the synchronization signal, and coupled to receive the N outputs from the shift register, the logic circuit sequentially generating N clock-domain signals on respective outputs responsive to active shift signals from the shift register when the synchronization signal is active, and driving all clock-domain signals inactive when the synchronization signal is inactive;
- a first storage circuit having a reset input coupled to the output of the first reset circuit and set input coupled to the Nth output of the shift register, and developing an active never-calibrated signal on an output when the first reset signal goes active and an inactive never-calibrated signal when the Nth output goes active; and
- a second reset circuit having an output coupled to the reset terminal of the shift register circuit and developing on the output an active second reset signal when the clock-domain reset signal goes active, or the synchronization signal goes inactive and the Nth output of the shift register is active, or the synchronization signal goes inactive and the never-calibrated signal is active.

**16.** The system of claim **12** wherein the plurality of clock control circuits includes three clock control circuits developing respective command, first data clock, and second data clock signals responsive to external command clock, first data clock, and second data clock signals, respectively.

**17.** The system of claim **12** wherein each of the evaluation circuits compares each of the received digital signals to a predetermined value, and the results signal indicates whether each of the digital signals has the corresponding predetermined value.

**18.** A packetized dynamic random access memory, comprising:

- a plurality of clock generator circuits, each clock generator circuit controlling the phase of a respective internal clock signal relative to a corresponding external clock signal responsive to a respective phase command signal;
- at least one array of memory cells storing data at a location determined by a row address and a column address;
- a row address circuit receiving and decode the row address, and select a row of memory cells corresponding to the row address responsive to a first set of command signals;
- a column address circuit receiving or apply data to one of the memory cells in the selected row corresponding to the column address responsive to a second set of command signals;
- a data path circuit coupling data between an external terminal and the column address circuit responsive to a third set of command signals, and having a latch receiving a selected one of the internal clock signals from corresponding clock generators, and latching data packets applied on the data bus responsive to the selected clock signal;
- a command buffer receiving command packets and initialization packets having a predetermined value, the command buffer including a latch storing each of the received packets responsive to a transition of the internal clock signal, the command buffer further generating a respective command words and initialization words corresponding to each received command packet and initialization packet, respectively; and
- a synchronization circuit that adaptively adjusts the phases of the internal clock signals, each respective internal clock signal causing a corresponding latch to store a digital signal responsive to the respective internal clock signal, comprising,
  - a plurality of evaluation circuits coupled to respective latches, each evaluation circuit receiving a plurality of digital signals sequentially stored in the corresponding latch and generating a results signal indicating whether each of the digital signals has an expected value when a corresponding clock domain signal is active,
  - a phase selector circuit operating in a storage mode to sequentially develop a plurality of phase command signals on an output and store corresponding results signals sequentially received on an input, and operating in an analysis mode to develop on the output a final phase command signal from the stored results signals,
  - a plurality of storage circuits coupled to respective clock generator circuits and to the output of the phase selector circuit, each storage circuit storing the final phase command signal responsive to a corresponding clock domain signal, and
  - a clock-domain control circuit receiving a synchronization signal and coupled to the evaluation, storage, and phase selector circuits, the clock-domain circuit developing a plurality of clock domain signals to control the evaluation, storage, and phase selector circuits to sequentially synchronize each internal clock signal by storing a final phase command signal in the corresponding storage circuit, the time-domain control circuit operable when the synchronization signal goes inactive before all internal clock signals have been synchronized to retain existing final phase

command signals in the corresponding storage circuits, and to thereafter, when the synchronization signal again goes active, synchronize only those clock domains not synchronized during the previous cycle of the synchronization signal.

19. The packetized dynamic random access memory of claim 18 wherein the clock-domain control circuit further operates after the occurrence of a predetermined condition of the system to first determine final phase command signals for all internal clock signals during an active cycle of the synchronization signal until all clock signals are synchronized during a given cycle, and thereafter operates to determine final phase command signals only for those internal clock signals not synchronized during the previous active of the synchronization signal.

20. The packetized dynamic random access memory of claim 19 wherein the predetermined condition includes a reset signal going active.

21. The packetized dynamic random access memory of claim 18 wherein the clock-domain control circuit comprises:

- a pulse terminal receiving a pulse signal;
- a first reset circuit having inputs receiving at least one external reset signal and developing on an output an active clock-domain reset signal when any of the at least one external reset signal goes active;
- a shift register having an input coupled to a first voltage, N outputs, a clock terminal coupled to the pulse terminal, and a reset terminal, the shift register developing shift signals on respective outputs responsive to the pulse signal and resetting all shift signals responsive to the reset signal;
- a logic circuit including an enable terminal receiving the synchronization signal, and coupled to receive the N outputs from the shift register, the logic circuit sequentially generating N clock-domain signals on respective outputs responsive to active shift signals from the shift register when the synchronization signal is active, and driving all clock-domain signals inactive when the synchronization signal is inactive;
- a first storage circuit having a reset input coupled to the output of the first reset circuit and set input coupled to the Nth output of the shift register, and developing an active never-calibrated signal on an output when the first reset signal goes active and an inactive never-calibrated signal when the Nth output goes active; and
- a second reset circuit having an output coupled to the reset terminal of the shift register circuit and developing on the output an active second reset signal when the clock-domain reset signal goes active, or the synchronization signal goes inactive and the Nth output of the shift register is active, or the synchronization signal goes inactive and the never-calibrated signal is active.

22. The packetized dynamic random access memory of claim 18 wherein the plurality of clock generator circuits includes three clock control circuits developing respective command, first data clock, and second data clock signals responsive to external command clock, first data clock, and second data clock signals, respectively.

23. The packetized dynamic random access memory of claim 18 wherein each of the evaluation circuits compares each of the received digital signals to a predetermined value, and the results signal indicates whether each of the digital signals has the corresponding predetermined value.

24. An integrated circuit receiving a plurality of input signals and generate a plurality of output signals on respective, externally accessible terminals, comprising:

a plurality of clock generator circuits, each clock generator circuit controlling the phase of a respective internal clock signal relative to a corresponding external clock signal responsive to a respective phase command signal;

a circuit receiving a plurality of input signals applied to respective other of the terminals and to generate a plurality of output signals on respective other of the terminals;

a plurality of latches, each latch coupled to one of the terminals and receiving an input signal and store an input signal applied to the terminal responsive to a transition of a corresponding one of the internal clock signals; and

a synchronization circuit that adaptively adjusts the phases of the internal clock signals, each respective internal clock signal causing a corresponding latch to store a digital signal responsive to the respective internal clock signal, comprising,

a plurality of evaluation circuits coupled to respective latches, each evaluation circuit receiving a plurality of digital signals sequentially stored in the corresponding latch and generating a results signal indicating whether each of the digital signals has an expected value when a corresponding clock domain signal is active,

a phase selector circuit operating in a storage mode to sequentially develop a plurality of phase command signals on an output and store corresponding results signals sequentially received on an input, and operating in an analysis mode to develop on the output a final phase command signal from the stored results signals,

a plurality of storage circuits coupled to respective clock generator circuits and to the output of the phase selector circuit, each storage circuit storing the final phase command signal responsive to a corresponding clock domain signal, and

a clock-domain control circuit receiving a synchronization signal and coupled to the evaluation, storage, and phase selector circuits, the clock-domain circuit developing a plurality of clock domain signals to control the evaluation, storage, and phase selector circuits to sequentially synchronize each internal clock signal by storing a final phase command signal in the corresponding storage circuit, the clock-domain control circuit operable when the synchronization signal goes inactive before all internal clock signals have been synchronized to retain existing final phase command signals in the corresponding storage circuits, and to thereafter, when the synchronization signal again goes active, synchronize only those clock domains not synchronized during the previous cycle of the synchronization signal.

25. The integrated circuit of claim 24 wherein the clock-domain control circuit further operates after the occurrence of a predetermined condition of the system to first determine final phase command signals for all internal clock signals during an active cycle of the synchronization signal until all clock signals are synchronized during a given cycle, and thereafter operates to determine final phase command signals only for those internal clock signals not synchronized during the previous active of the synchronization signal.

26. The integrated circuit of claim 25 wherein the predetermined condition includes a reset signal going active.

27. The integrated circuit of claim 24 wherein the clock-domain control circuit comprises:

45

a pulse terminal receiving a pulse signal;

a first reset circuit having inputs receiving at least one external reset signal and developing on an output an active clock-domain reset signal when any of the at least one external reset signal goes active;

a shift register having an input coupled to a first voltage, N outputs, a clock terminal coupled to the pulse terminal, and a reset terminal, the shift register developing shift signals on respective outputs responsive to the pulse signal and resetting all shift signals responsive to the reset signal;

a logic circuit including an enable terminal receiving the synchronization signal, and coupled to receive the N outputs from the shift register, the logic circuit sequentially generating N clock-domain signals on respective outputs responsive to active shift signals from the shift register when the synchronization signal is active, and driving all clock-domain signals inactive when the synchronization signal is inactive;

a first storage circuit having a reset input coupled to the output of the first reset circuit and set input coupled to the Nth output of the shift register, and developing an active never-calibrated signal on an output when the first reset signal goes active and an inactive never-calibrated signal when the Nth output goes active; and

a second reset circuit having an output coupled to the reset terminal of the shift register circuit and developing on the output an active second reset signal when the clock-domain reset signal goes active, or the synchronization signal goes inactive and the Nth output of the shift register is active, or the synchronization signal goes inactive and the never-calibrated signal is active.

**28.** The integrated circuit of claim **24** wherein the plurality of clock control circuits includes three clock control circuits developing respective command, first data clock, and second data clock signals responsive to external command clock, first data clock, and second data clock signals, respectively.

**29.** The integrated circuit of claim **24** wherein each of the evaluation circuits compares each of the received digital signals to a predetermined value, and the results signal indicates whether each of the digital signals has the corresponding predetermined value.

**30.** A computer system, comprising:

a processor having a processor bus;

an input device coupled to the processor through the processor bus to allow data to be entered into the computer system;

an output device coupled to the processor through the processor bus to allow data to be output from the computer system; and

a dynamic random access memory coupled to the processor bus to allow data to be stored, the dynamic random access memory receiving a plurality of input signals and generating a plurality of output signals on respective, externally accessible terminals, the dynamic random access memory, comprising,

a plurality of clock generator circuits, each clock generator circuit controlling the phase of a respective internal clock signal relative to a corresponding external clock signal responsive to a respective phase command signal;

at least one array of memory cells storing data at a location determined by a row address and a column address;

a row address circuit receiving and decoding the row address, and selecting a row of memory cells corre-

46

sponding to the row address responsive to a first set of command signals;

a column address circuit receiving or applying data to one of the memory cells in the selected row corresponding to the column address responsive to a second set of command signals;

a data path circuit coupling data between an external terminal and the column address circuit responsive to a third set of command signals, and having a latch receiving a selected one of the internal clock signals from corresponding clock generators, and latching data packets applied on the data bus responsive to the selected clock signal;

a command buffer receiving command packets and initialization packets having a predetermined value, the command buffer including a latch storing each of the received packets responsive to a transition of the internal clock signal, the command buffer further generating a respective command words and initialization words corresponding to each received command packet and initialization packet, respectively; and

a synchronization circuit that adaptively adjusts the phases of the internal clock signals, each respective internal clock signal causing a corresponding latch to store a digital signal responsive to the respective internal clock signal, comprising,

a plurality of evaluation circuits coupled to respective latches, each evaluation circuit receiving a plurality of digital signals sequentially stored in the corresponding latch and generating a results signal indicating whether each of the digital signals has an expected value when a corresponding clock domain signal is active,

a phase selector circuit operating in a storage mode to sequentially develop a plurality of phase command signals on an output and store corresponding results signals sequentially received on an input, and operating in an analysis mode to develop on the output a final phase command signal from the stored results signals,

a plurality of storage circuits coupled to respective clock generator circuits and to the output of the phase selector circuit, each storage circuit storing the final phase command signal responsive to a corresponding clock domain signal, and

a clock-domain control circuit receiving a synchronization signal and coupled to the evaluation, storage, and phase selector circuits, the clock-domain circuit developing a plurality of clock domain signals to control the evaluation, storage, and phase selector circuits to sequentially synchronize each internal clock signal by storing a final phase command signal in the corresponding storage circuit, the clock-domain control circuit operable when the synchronization signal goes inactive before all internal clock signals have been synchronized to retain existing final phase command signals in the corresponding storage circuits, and to thereafter, when the synchronization signal again goes active, synchronize only those clock domains not synchronized during the previous cycle of the synchronization signal.

**31.** The computer system of claim **30** wherein the clock-domain control circuit further operates after the occurrence of a predetermined condition of the system to first determine final phase command signals for all internal clock signals

47

during an active cycle of the synchronization signal until all clock signals are synchronized during a given cycle, and thereafter operates to determine final phase command signals only for those internal clock signals not synchronized during the previous active of the synchronization signal. 5

**32.** The computer system of claim **31** wherein the predetermined condition includes a reset signal going active.

**33.** The computer system of claim **30** wherein the clock-domain control circuit comprises:

- a pulse terminal receiving a pulse signal; 10
- a first reset circuit having inputs receiving at least one external reset signal and developing on an output an active clock-domain reset signal when any of the at least one external reset signal goes active;
- a shift register having an input coupled to a first voltage, N outputs, a clock terminal coupled to the pulse terminal, and a reset terminal, the shift register developing shift signals on respective outputs responsive to the pulse signal and resetting all shift signals responsive to the reset signal; 15
- a logic circuit including an enable terminal receiving the synchronization signal, and coupled to receive the N outputs from the shift register, the logic circuit sequentially generating N clock-domain signals on respective outputs responsive to active shift signals from the shift register when the synchronization signal is active, and driving all clock-domain signals inactive when the synchronization signal is inactive; 25

48

a first storage circuit having a reset input coupled to the output of the first reset circuit and set input coupled to the Nth output of the shift register, and developing an active never-calibrated signal on an output when the first reset signal goes active and an inactive never-calibrated signal when the Nth output goes active; and

a second reset circuit having an output coupled to the reset terminal of the shift register circuit and developing on the output an active second reset signal when the clock-domain reset signal goes active, or the synchronization signal goes inactive and the Nth output of the shift register is active, or the synchronization signal goes inactive and the never-calibrated signal is active.

**34.** The computer system of claim **30** wherein the plurality of clock control circuits includes three clock control circuits developing respective command, first data clock, and second data clock signals responsive to external command clock, first data clock, and second data clock signals, respectively.

**35.** The computer system of claim **30** wherein each of the evaluation circuits compares each of the received digital signals to a predetermined value, and the results signal indicates whether each of the digital signals has the corresponding predetermined value.

\* \* \* \* \*

UNITED STATES PATENT AND TRADEMARK OFFICE  
**CERTIFICATE OF CORRECTION**

PATENT NO. : 6,338,127 B1  
DATED : January 8, 2002  
INVENTOR(S) : Troy A. Manning

Page 1 of 1

It is certified that error appears in the above-identified patent and that said Letters Patent is hereby corrected as shown below:

Title page,

Item [56], **References Cited,**

U.S. PATENT DOCUMENTS, reads "4,636,187 A" should read -- 4,638,187 A --  
FOREIGN PATENT DOCUMENTS, "EP 0767 538 A1" reference reads "4/1994"  
should read -- 4/1997 --; "2-11317" should read -- 2-112317 --  
OTHER PUBLICATIONS, "Microprocessor and Microprocessor" should read  
-- Microprocessor and Microcomputer --  
"Taguchi, M. et al." reference reads "40-ns-64-Mb" should read -- 40-ns 64-Mb --

Column 41,

Line 19, reads "active" should read -- active cycle --

Column 42,

Line 9, reads "decode" should read -- decoding --  
Line 13, reads "apply" should read -- applying --

Column 43,

Line 14, reads "active" should read -- active cycle --

Column 44,

Line 63, reads "active" should read -- active cycle --


Column 47,

Line 5, reads "active" should read -- active cycle --

Signed and Sealed this

Eighth Day of October, 2002

*Attest:*



*Attesting Officer*

JAMES E. ROGAN  
*Director of the United States Patent and Trademark Office*